Electron Neutrino Appearance Measurement in NOvA

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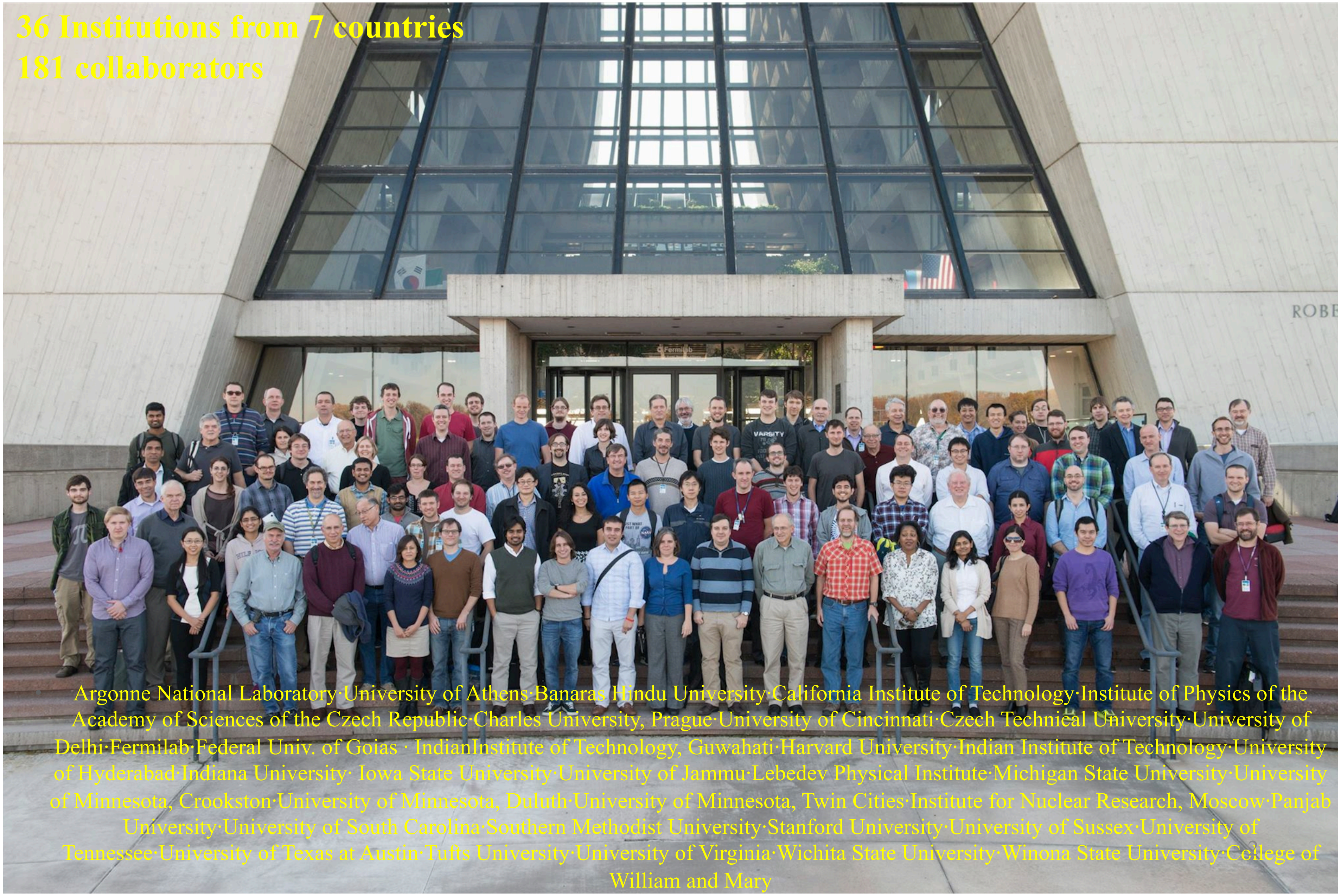
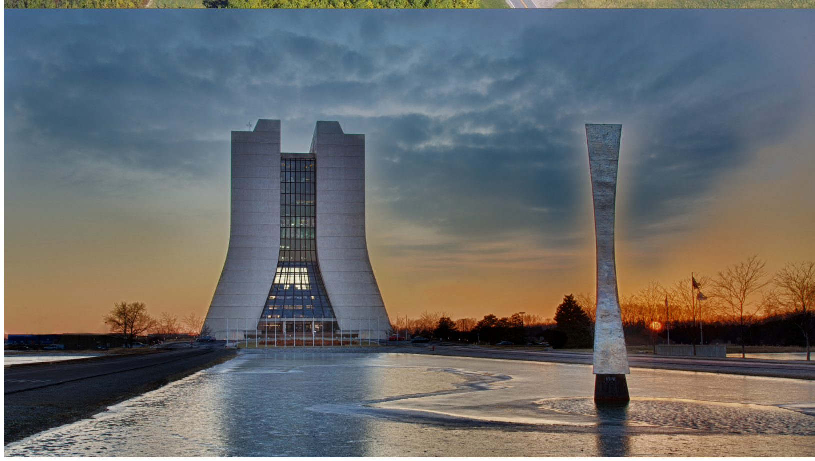
NOvA Collaboration



36 Institutions from 7 countries
181 collaborators

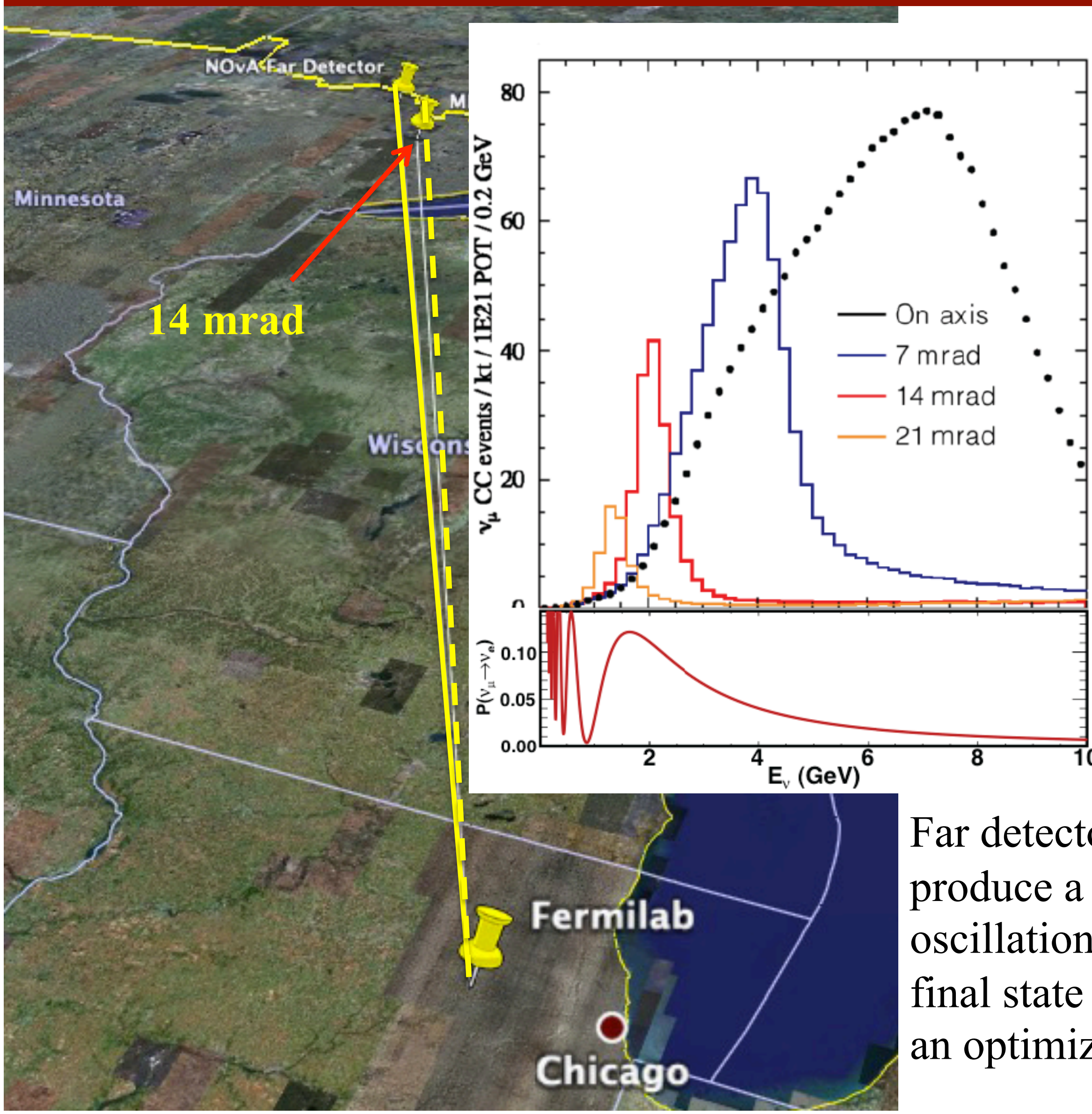
Argonne National Laboratory·University of Athens·Banaras Hindu University·California Institute of Technology·Institute of Physics of the Academy of Sciences of the Czech Republic·Charles University, Prague·University of Cincinnati·Czech Technical University·University of Delhi·Fermilab·Federal Univ. of Goias · IndianInstitute of Technology, Guwahati·Harvard University·Indian Institute of Technology·University of Hyderabad·Indiana University· Iowa State University·University of Jammu·Lebedev Physical Institute·Michigan State University·University of Minnesota, Crookston·University of Minnesota, Duluth·University of Minnesota, Twin Cities·Institute for Nuclear Research, Moscow·Panjab University·University of South Carolina·Southern Methodist University·Stanford University·University of Sussex·University of Tennessee·University of Texas at Austin·Tufts University·University of Virginia·Wichita State University·Winona State University·College of William and Mary

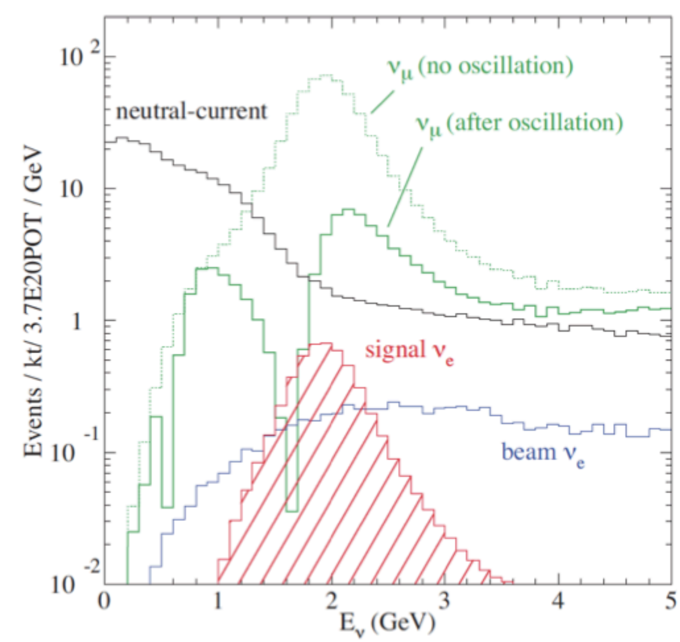
NuMI Off-Axis ν_e Appearance Experiment



- NOvA is a 2-detector ν oscillation experiment, optimized for ν_e identification.
- Upgrading NuMI muon neutrino beam at Fermilab (700 kW).
- Construct a 14 kt liquid scintillator far detector at a distance of 810 km (Ash river, Minnesota) to detect the oscillated beam.
- Functionally identical ~300 ton near detector located at Fermilab to measure unoscillated beam ν to estimate backgrounds in the far detector.

NuMI Off-Axis ν_e Appearance Experiment





Far detector is sited 14 mrad off-axis to produce a narrow-band beam around the oscillation maximum region. Combining with final state interaction cross sections, provides an optimized signal/background separation.

NOνA Physics Goals

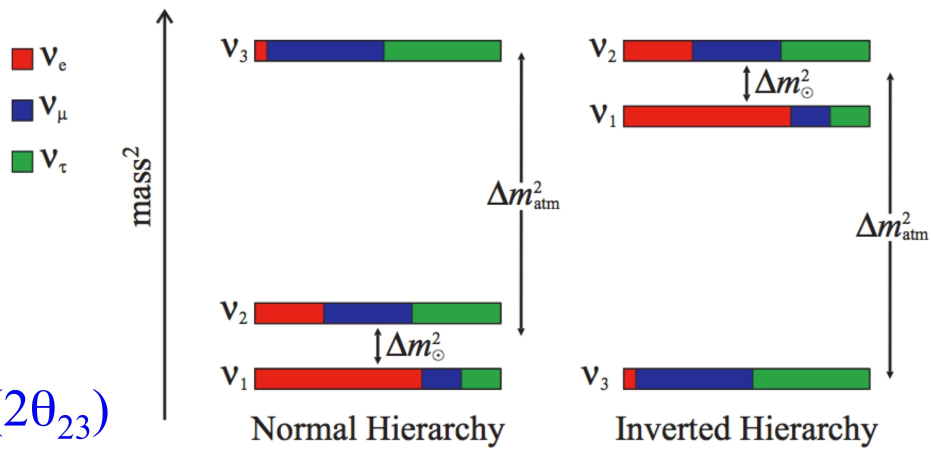
Measuring ν_e appearance probability and ν_μ disappearance probability with ν_u and anti-ν_u beam.

ν_e appearance:

- Measure θ_{13}
- Determine neutrino mass hierarchy
- Resolution of the θ_{23} octant.
- Constrain CP violation phase (δ_{CP})

ν_μ disappearance:

- Precise measurements of $|\Delta m_{32}{}^2|$, $\sin^2(2\theta_{23})$



As well as:

- ν cross sections.
- Neutrino magnetic moment.
- Supernova.
- monopoles.
- Sterile neutrinos.
- Non-standard neutrino interactions.

ν_e appearance at NOvA

$$P(\overset{(-)}{\nu}_\mu \to \overset{(-)}{\nu}_e) \approx \sin^2 2\theta_{13} \sin^2\theta_{23} \frac{\sin^2(A-1)\Delta}{(A-1)^2}$$
$$+2\alpha \sin\theta_{13} \cos\delta \sin 2\theta_{12} \sin 2\theta_{23} \frac{\sin A\Delta}{A} \frac{\sin(A-1)\Delta}{(A-1)} \cos\Delta$$
$$\overset{(+)}{-}2\alpha \sin\theta_{13} \sin\delta \sin 2\theta_{12} \sin 2\theta_{23} \frac{\sin A\Delta}{A} \frac{\sin(A-1)\Delta}{(A-1)} \sin\Delta$$

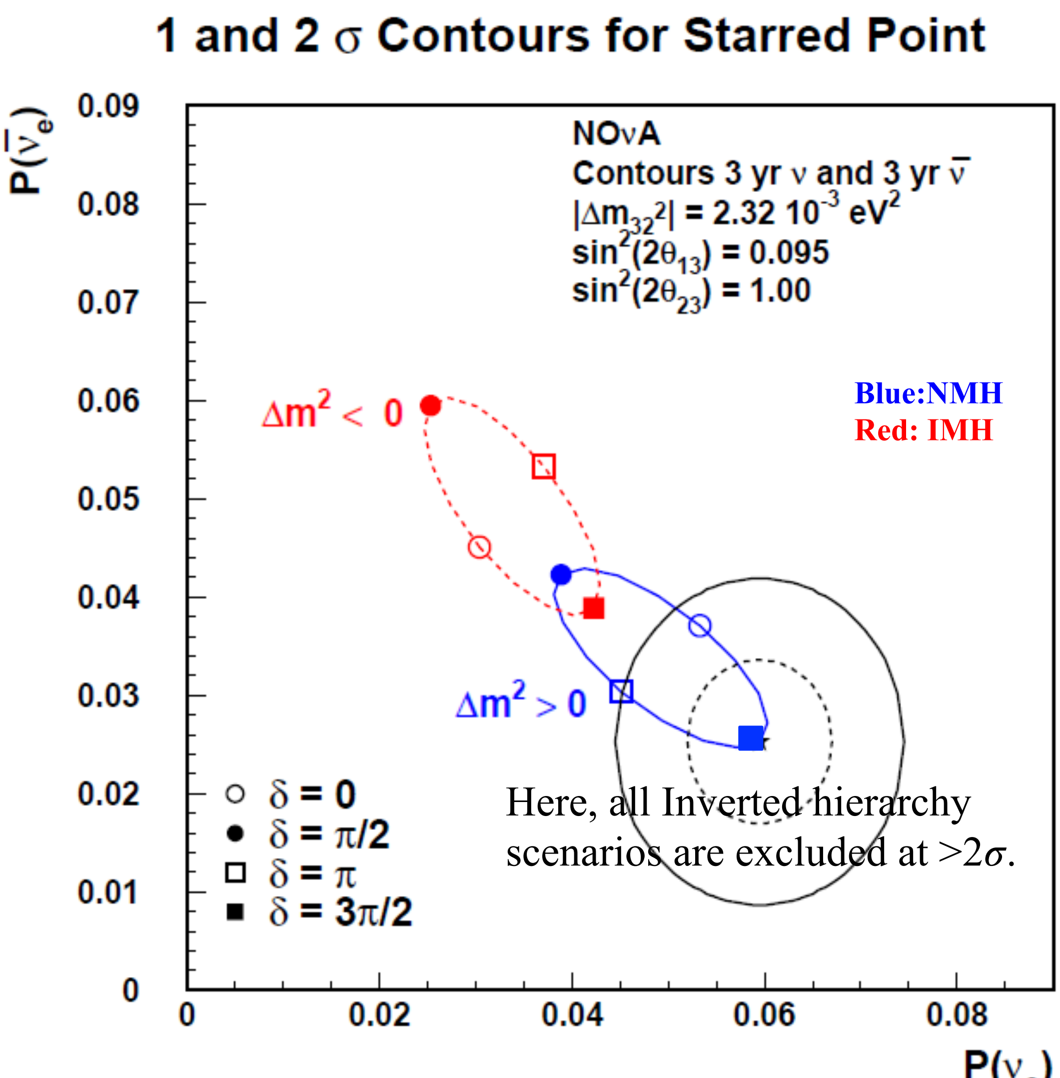
$$\Delta \equiv \frac{\Delta m^2_{31} L}{4E} \quad A = \overset{(-)}{+} G_f N_e \frac{L}{\sqrt{2}\Delta}$$

- We can investigate mass hierarchy due to θ_{13} is not zero.

- We have some sensitivity for δ_{CP} since θ_{13} is not zero.

- Probability is enhanced or suppressed due to matter effects which depend on the mass hierarchy as well as the sign of ***A*** which is determined by **neutrino vs. anti-neutrino** running.

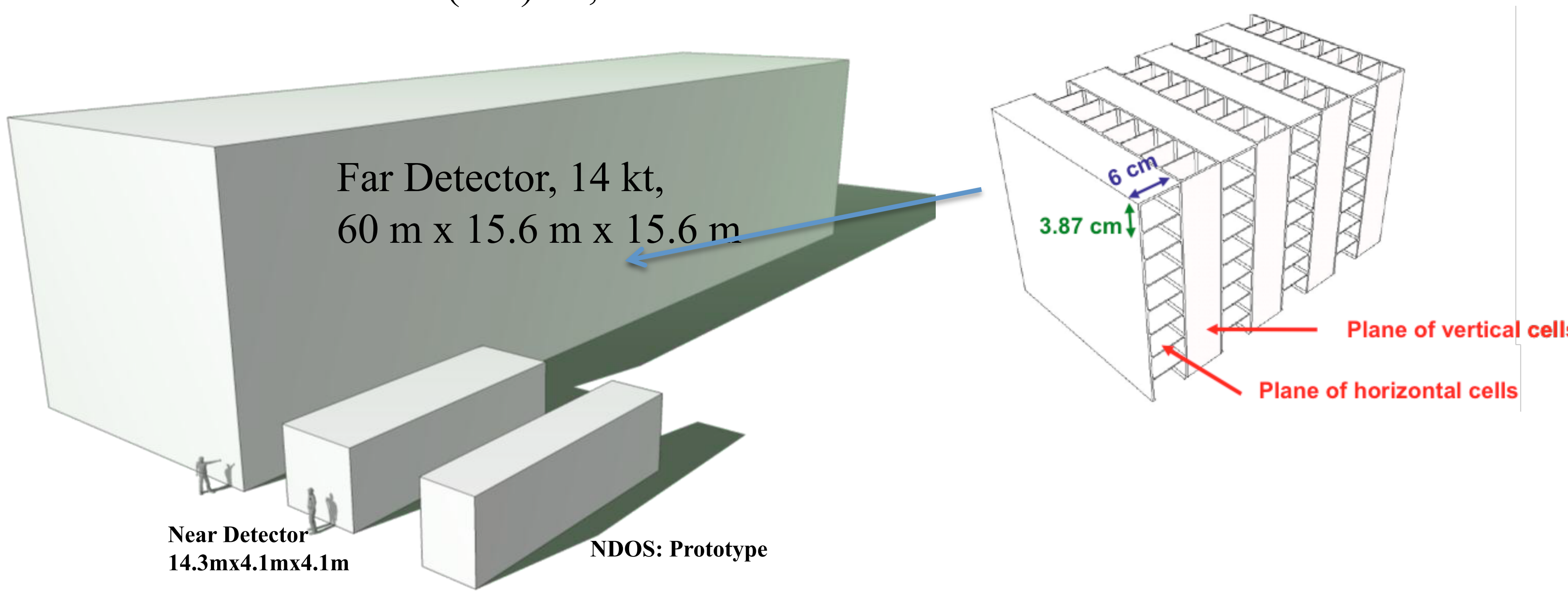
ν_e appearance at NOνA



- Because the $P(\nu_e)$ and $P(\bar{\nu}_e)$ depend on mass hierarchy and δ_{CP} in different ways, a measurement of the probabilities might allow resolving the mass hierarchy and provide information on δ_{CP}.
- The precision of probabilities measurement depends on θ_{13}. Large θ_{13} also reduces the overlap area of NMH and IMH ellipses. So it is good news for NOνA that θ_{13} is large.

The NOνA Detectors

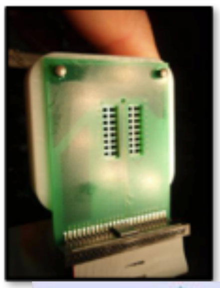
- 14-kton Far Detector (FD, "Largest plastic structure built by man".).
- 9-kton active detector.
- 344,064 detector cells read by APDs.
- 0.3 kton Near Detector (ND) 18,432 cells.



- Composed of PVC modules extruded to form long tube-like cells : 15m long in FD, 4m ND.
- Each cell is filled with liquid scintillator.
- Cells arranged in planes, assembled in alternating planes of vertical and horizontal extrusions.
- Each plane just 0.15 X_0. Great for e^- vs π^0 .

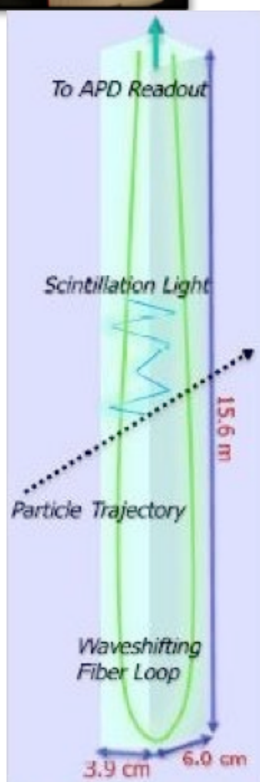
Detectors readout

32-pixel APD

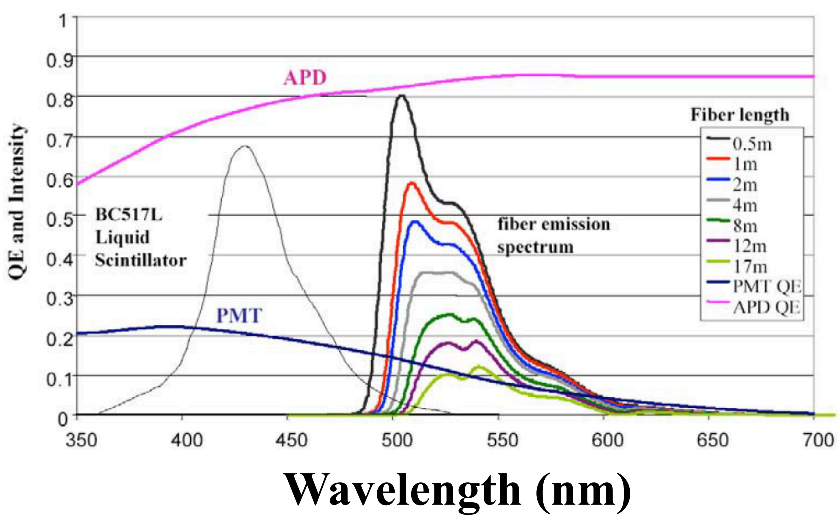


Fiber pairs from 32 cells

Each cell has a wavelength-shifting fiber routed an Avalanche Photodiode (APD). Scintillation light emitted isotropically and captured in wavelength -shifting fibers that convert wavelength to APD's sensitive region.



NOvA basic cell

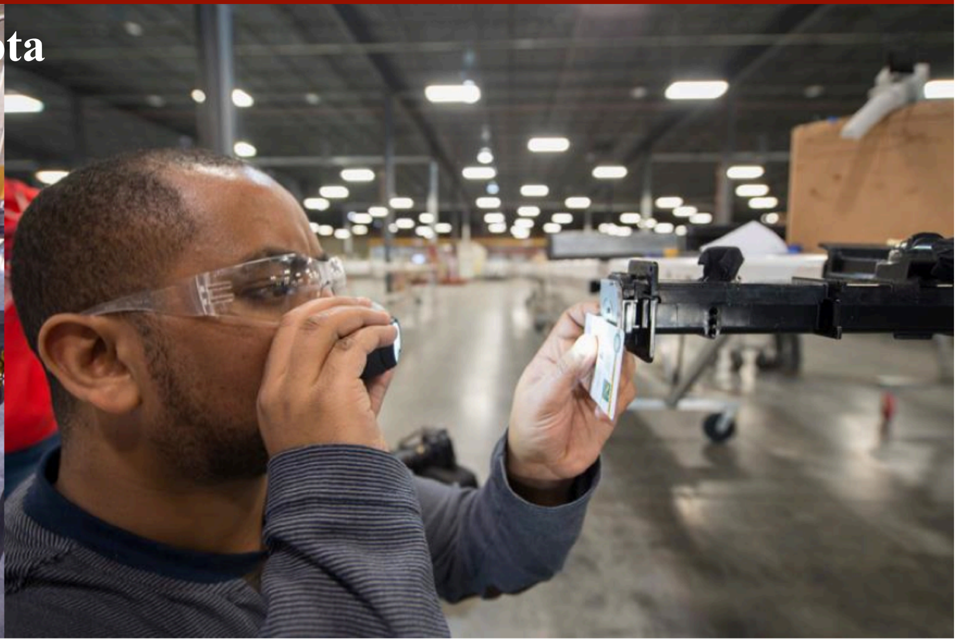


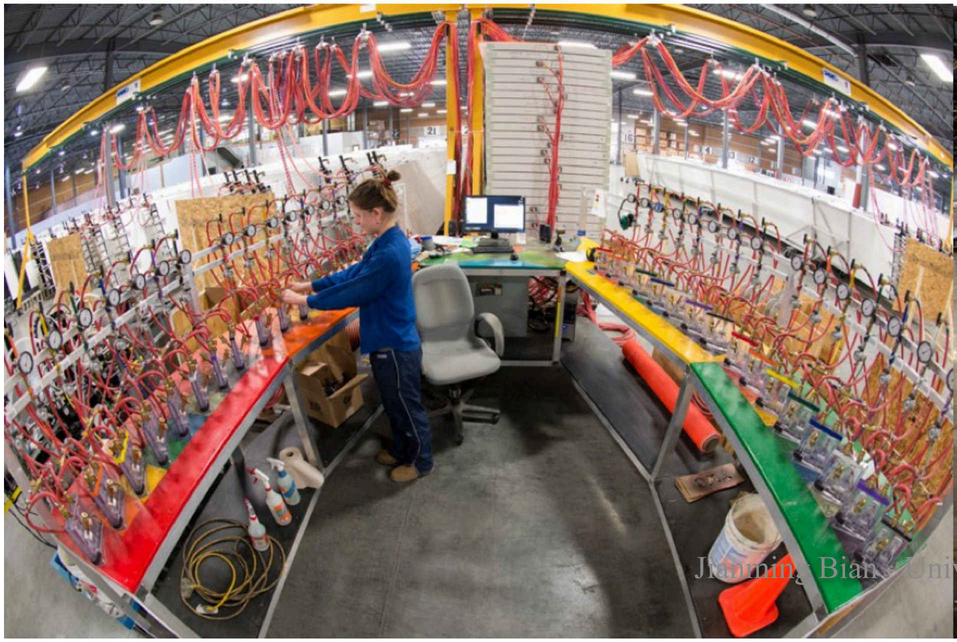
APDs have high quantum efficiency and uniform spectral quantum efficiency. This enables the use of very long scintillator modules, thus significantly reducing the electronics channel count.

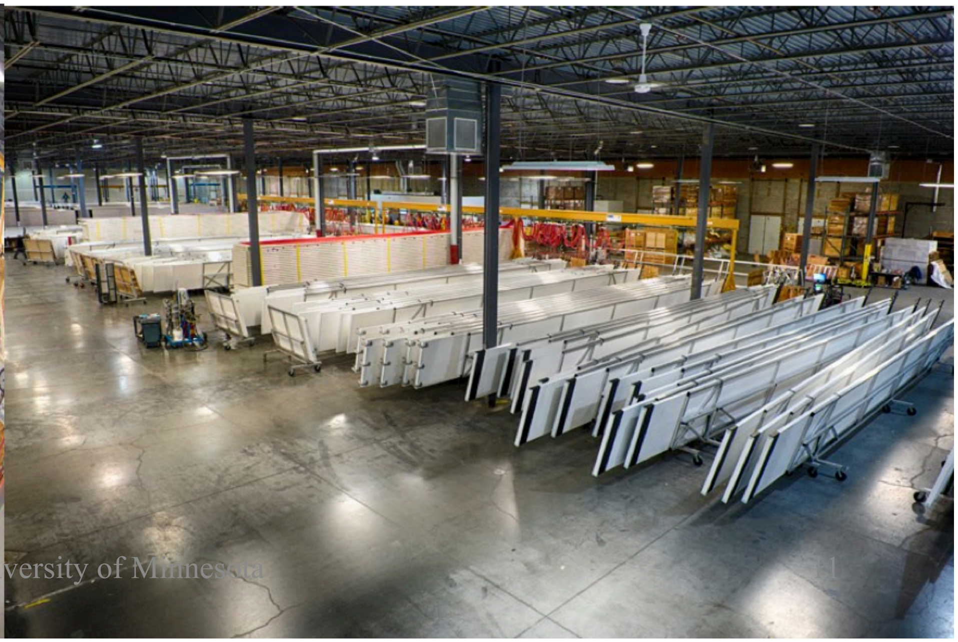
Far detector construction

Far detector construction

Module construction at University of Minnesota

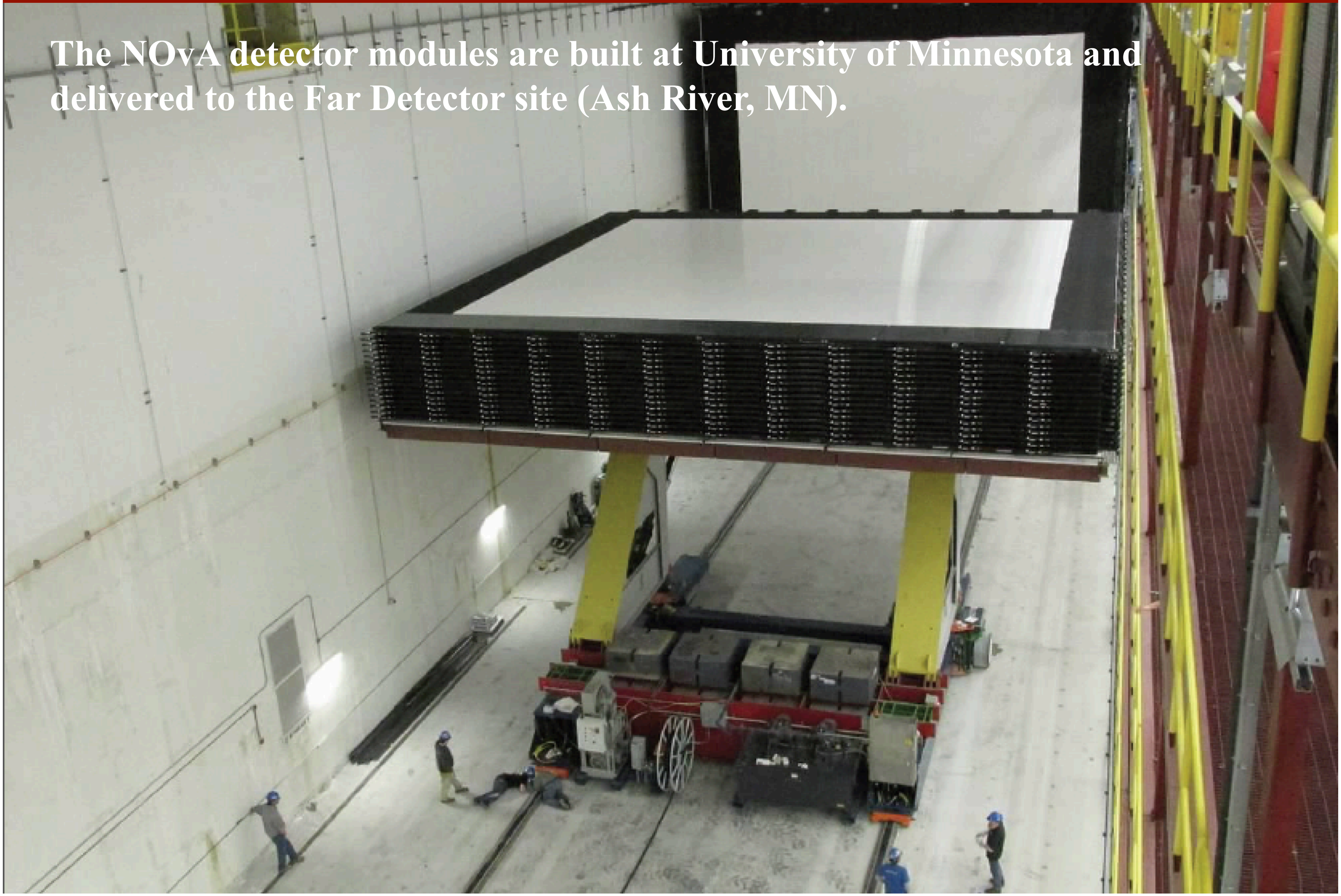






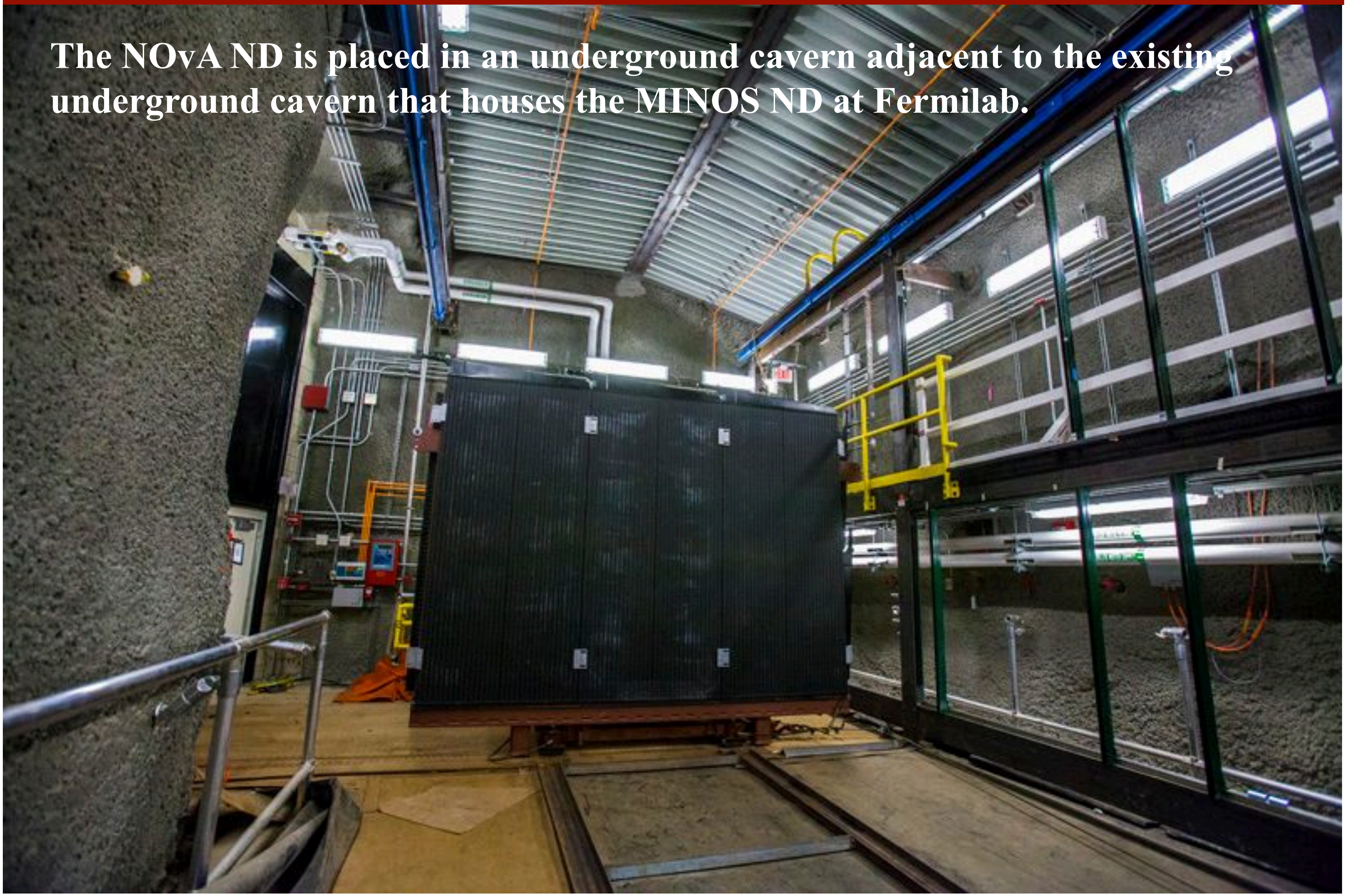
Far detector construction

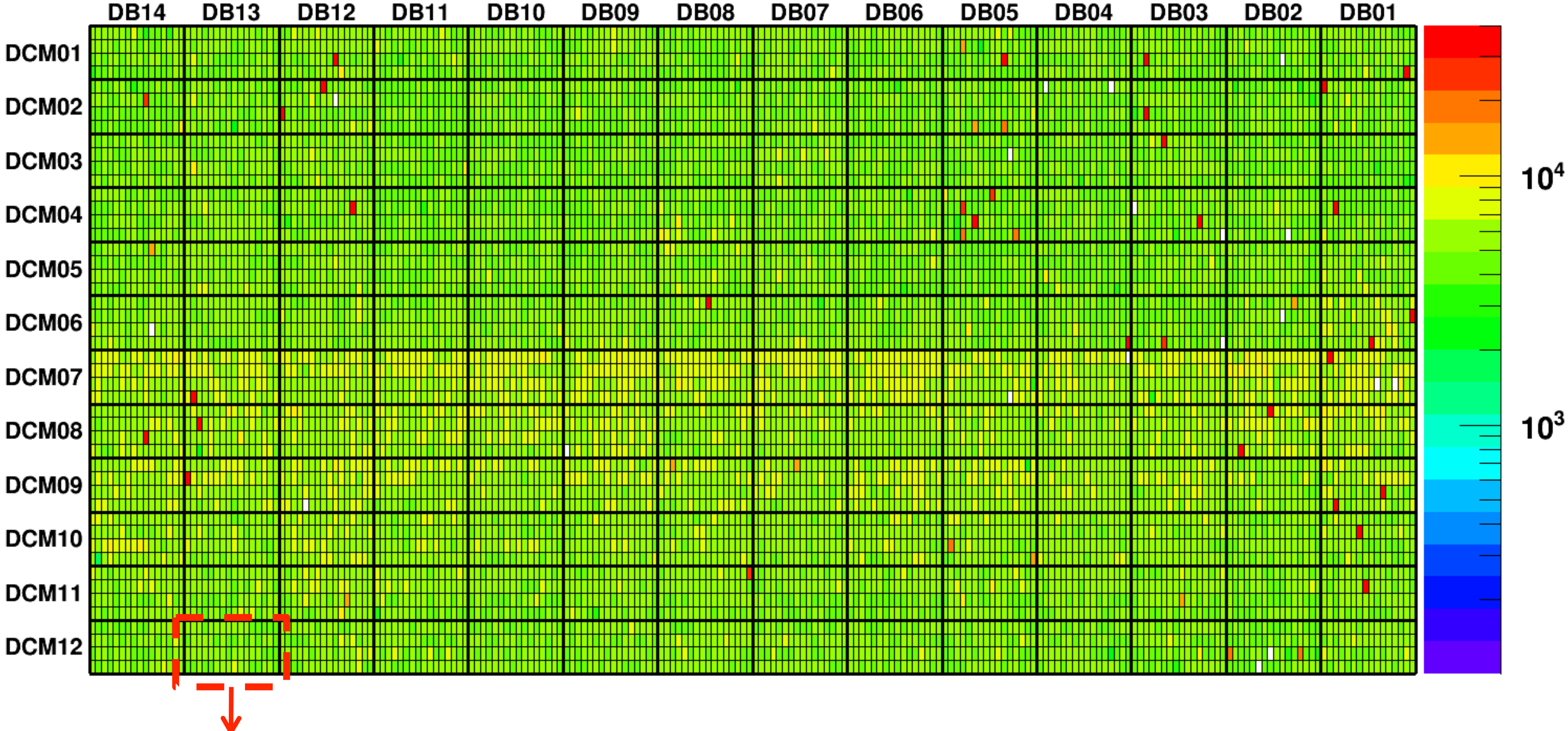
The NOvA detector modules are built at University of Minnesota and delivered to the Far Detector site (Ash River, MN).

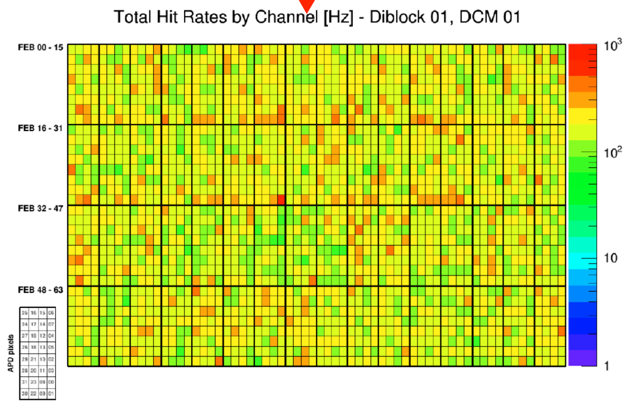


Near detector construction

The NOvA ND is placed in an underground cavern adjacent to the existing underground cavern that houses the MINOS ND at Fermilab.

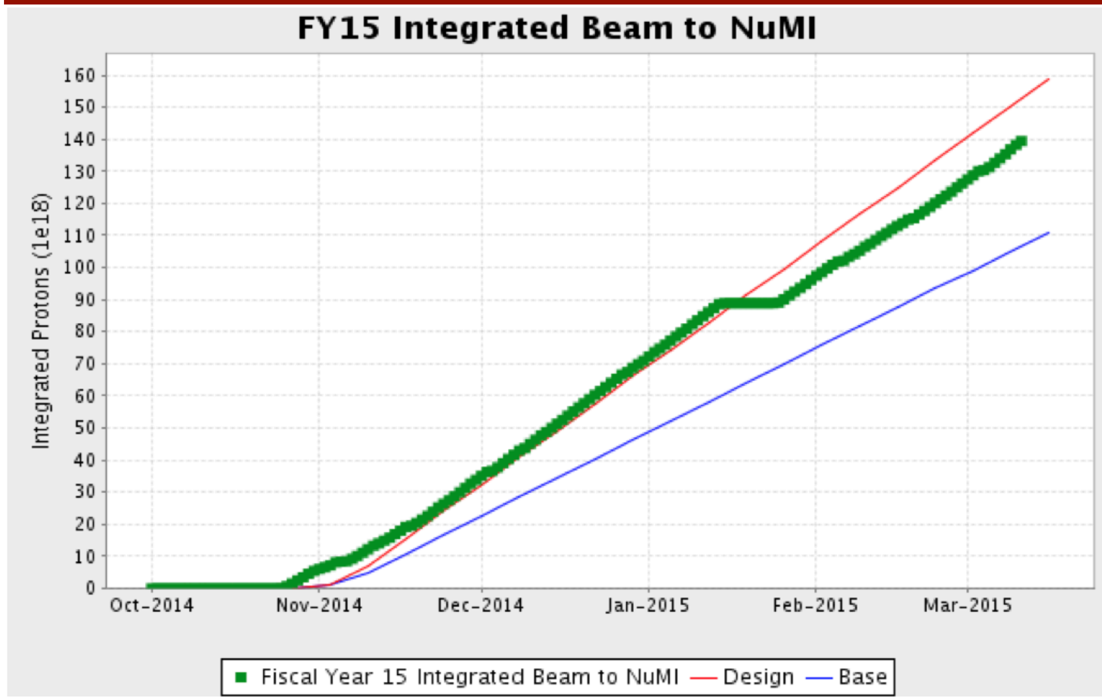


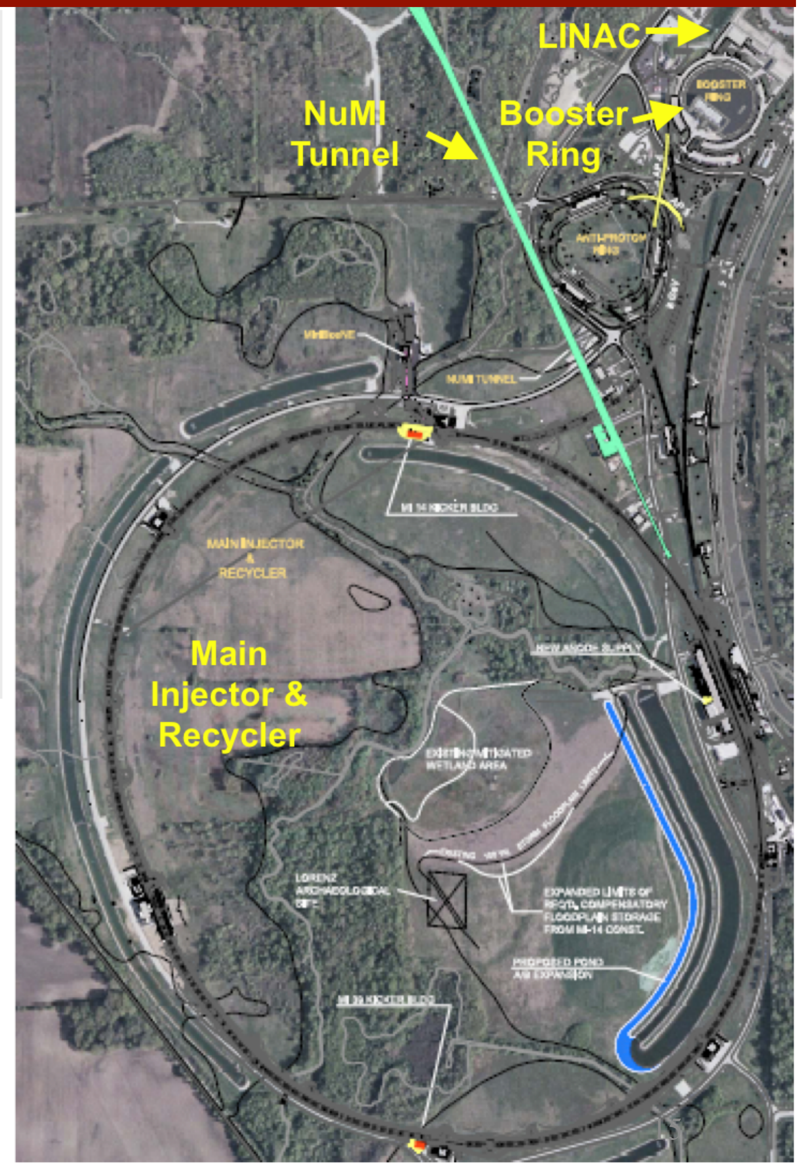




As of September 4th 2014, both far and near detectors are fully commissioned.

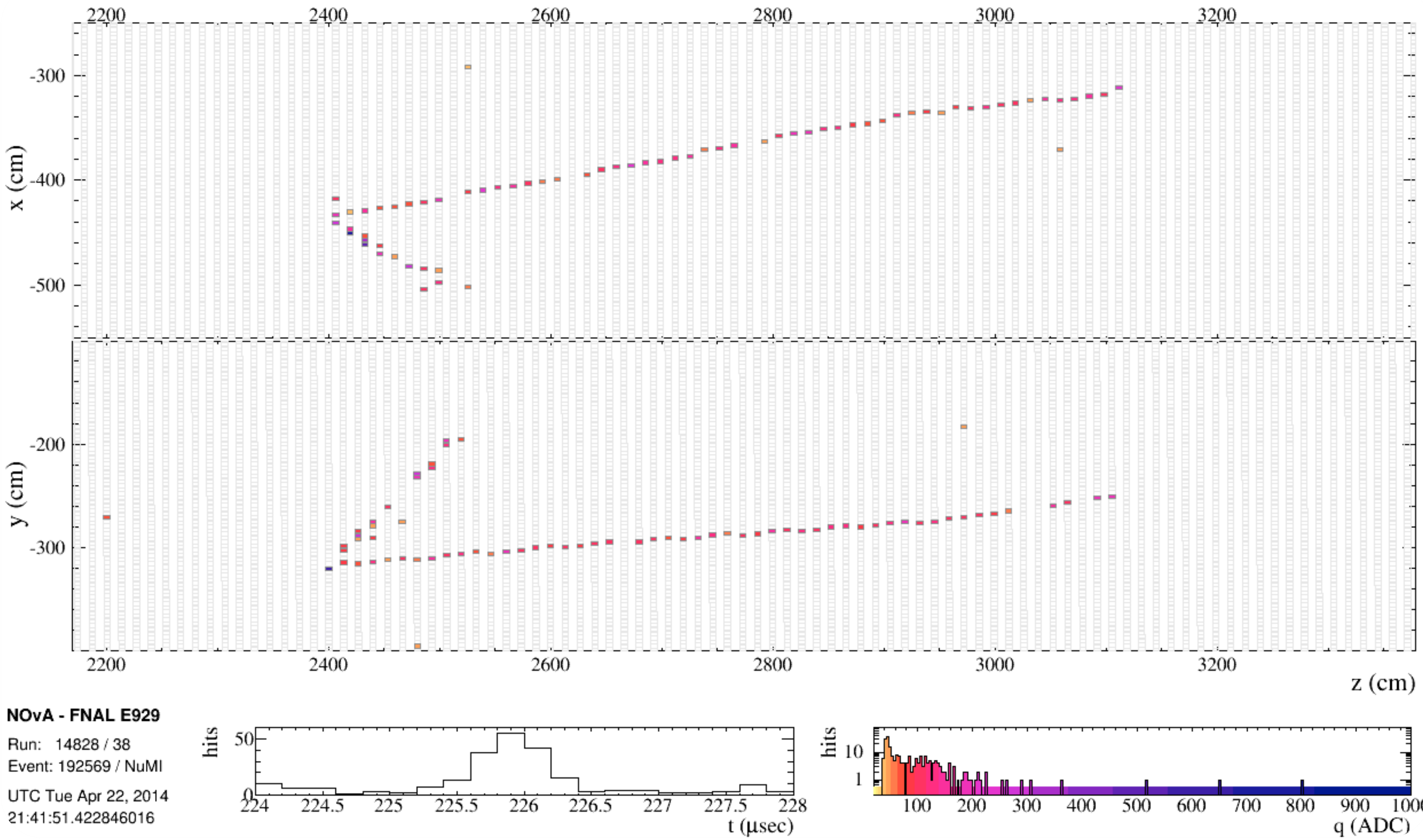
Accelerator and NuMI Upgrades



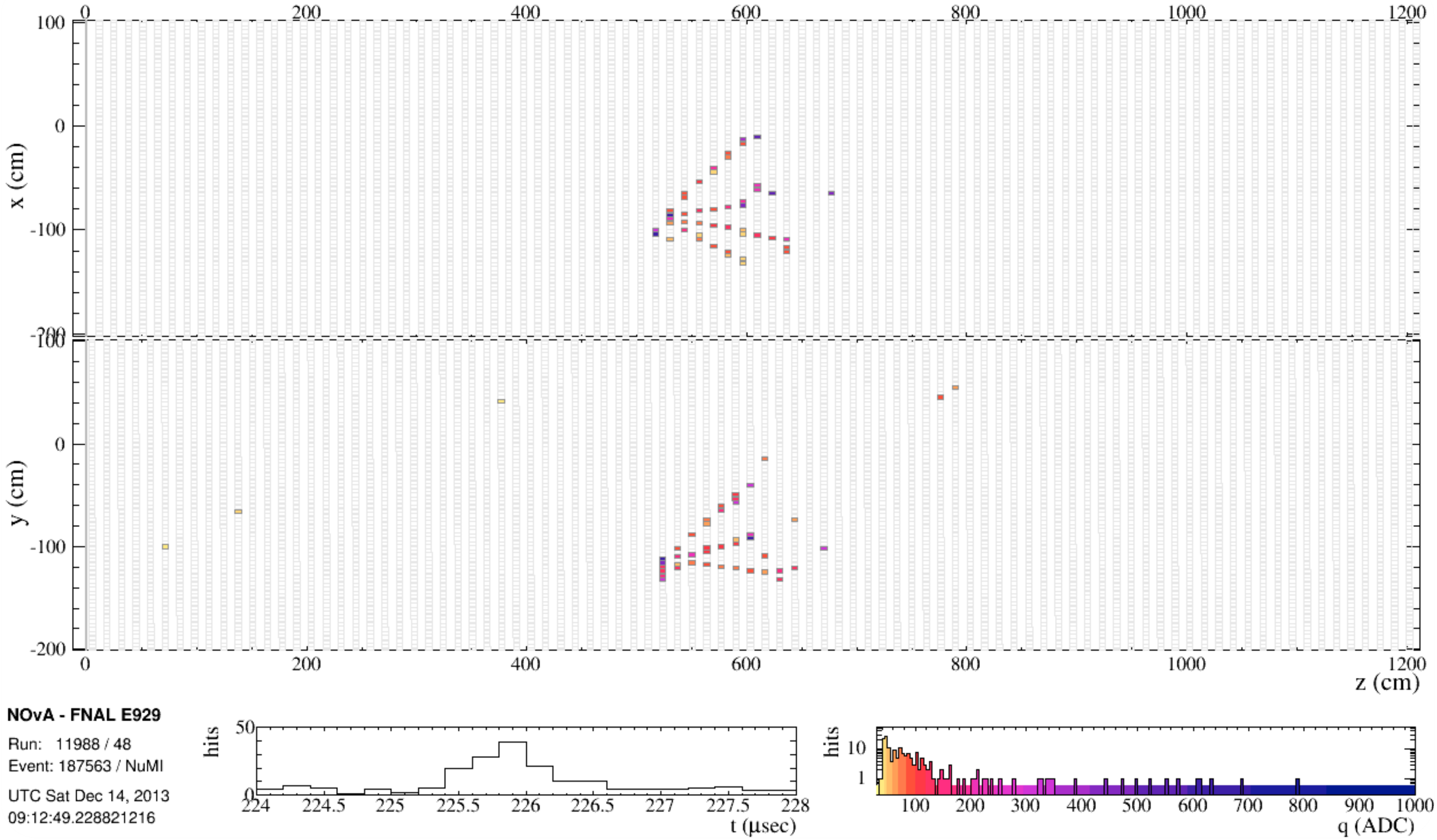


- Upgraded "Neutrinos at the Main Injector" (NuMI) accelerator complex:
  - We update the NuMI beam power from 320 kW to 700 kW.
  - Nominal NOvA year is 6×10^{20} protons on target (POT).
  - 3.3×10^{20} POT delivered since August 2013.
  - Beam power is ~360kW, will ramp up to 400kW soon.

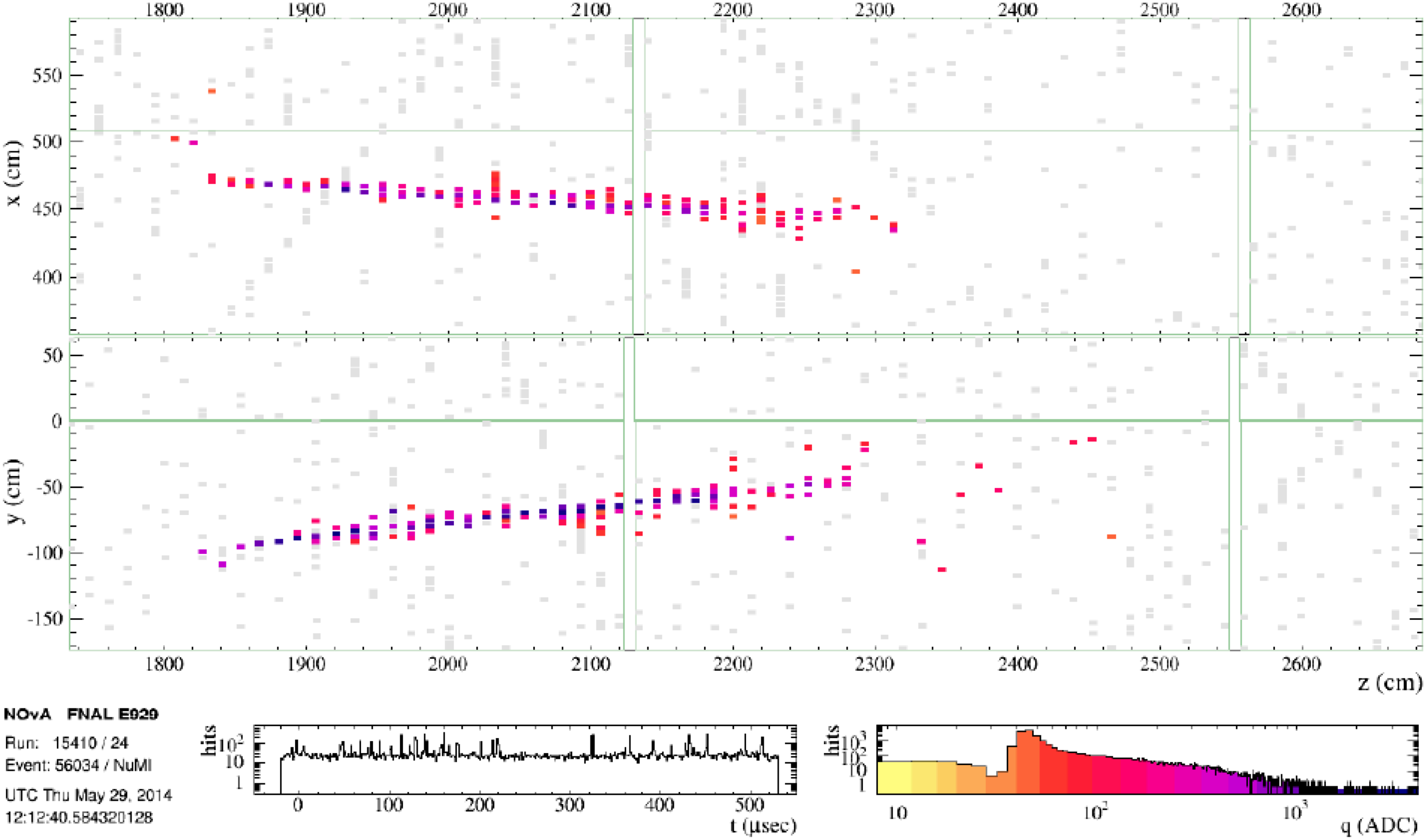
ν_μ-CC candidate in FD



NC candidate in FD

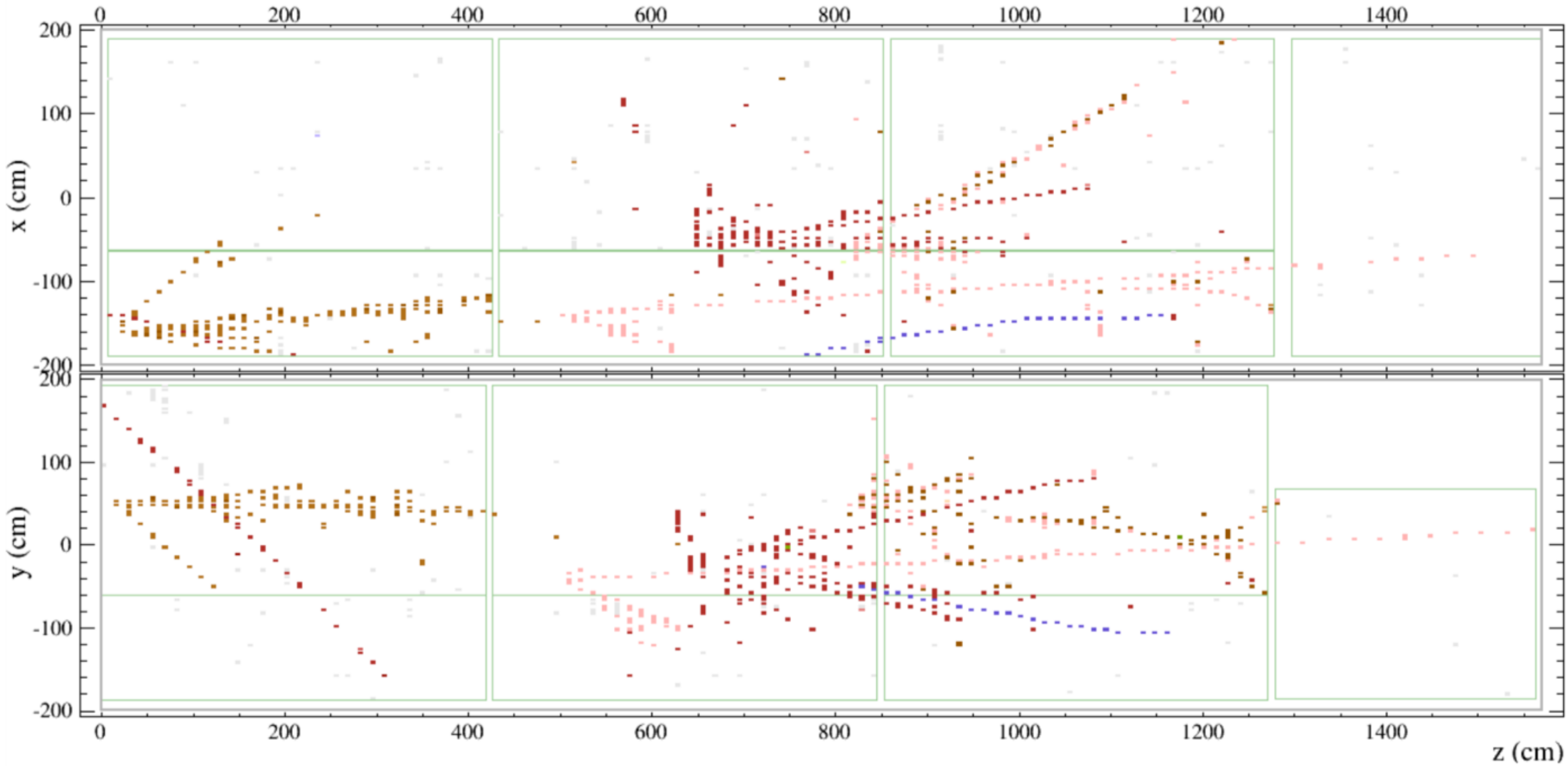


ν_e-CC candidate in FD?

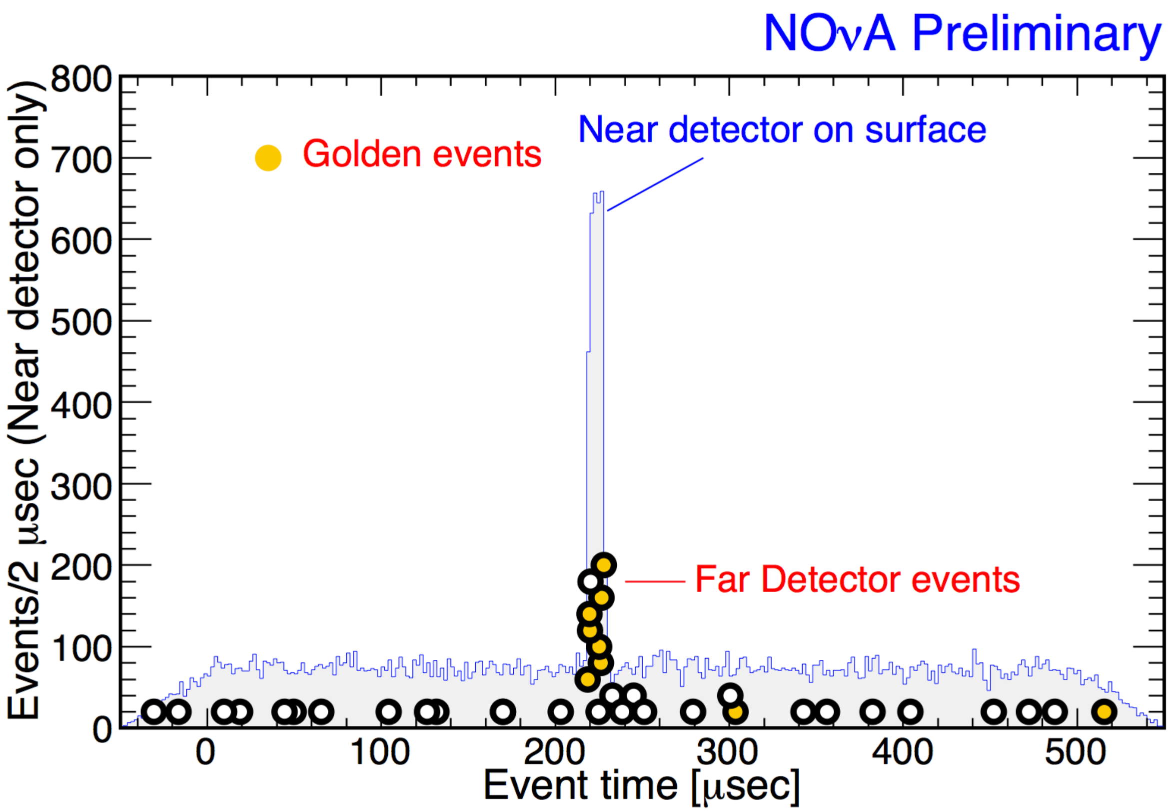


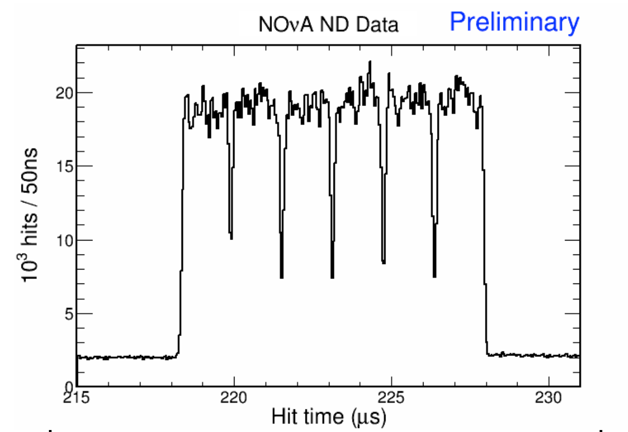
Neutrino candidates in ND

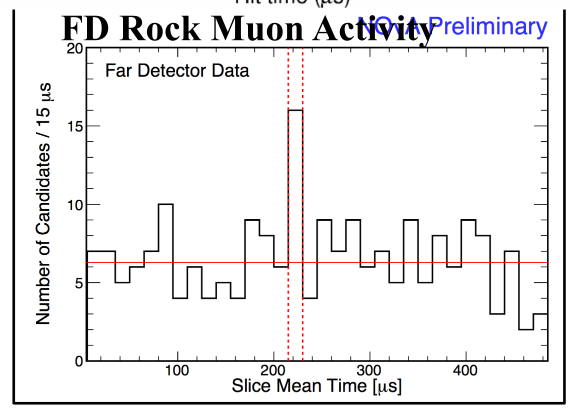
Because beam intensity is much higher in the near detector, there are more than one neutrinos in one trigger window.



Far/Near Detector ν timing





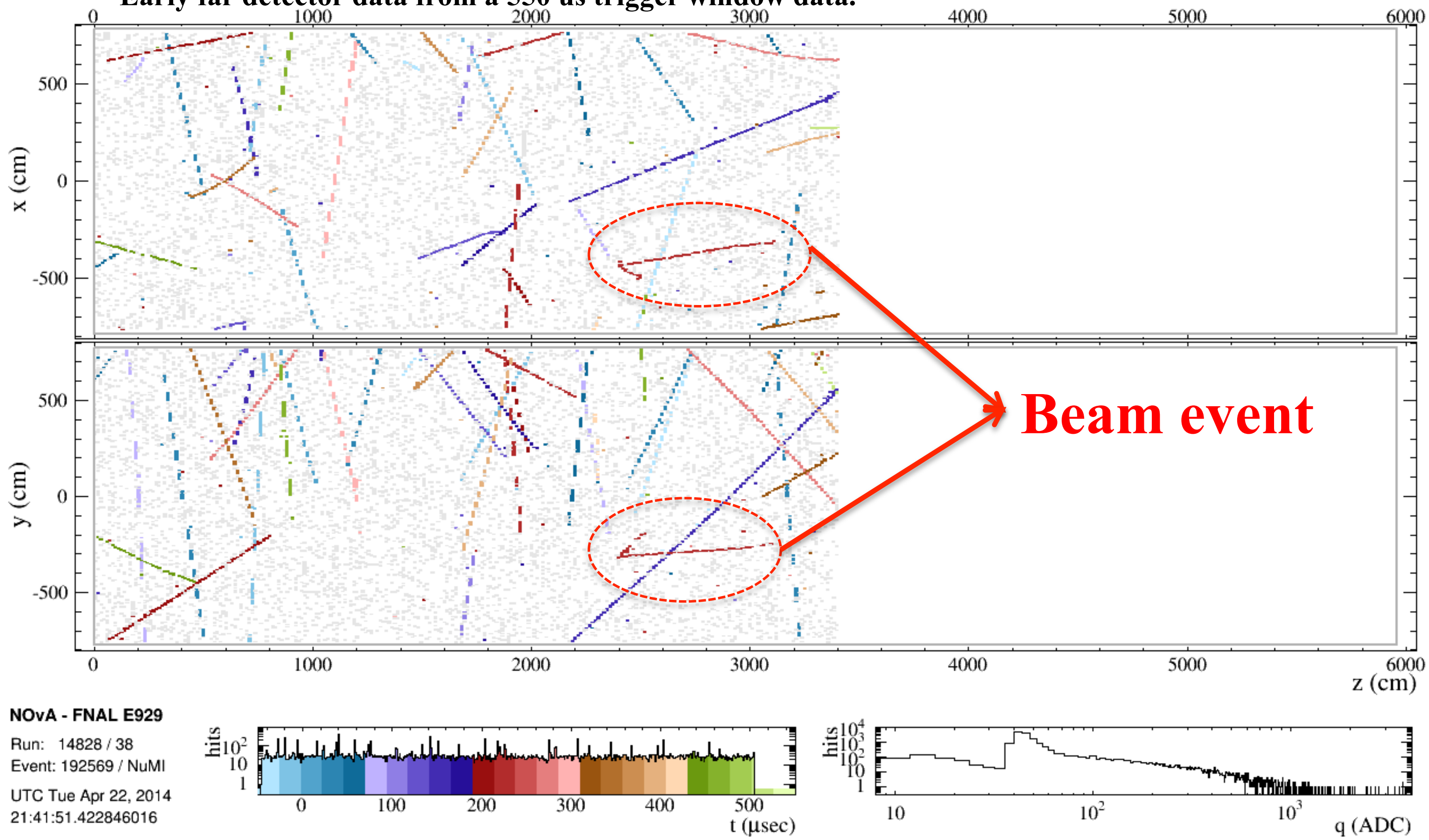


- Neutrino candidates are observed in both near and far detectors.
- FD neutrino candidates blow up of timing peak, showing agreement with expected spill times as measured at our surface detector at FNAL.
- Both FD & ND are nearly completed. NOvA is now taking data for physics.

Space-time clustering

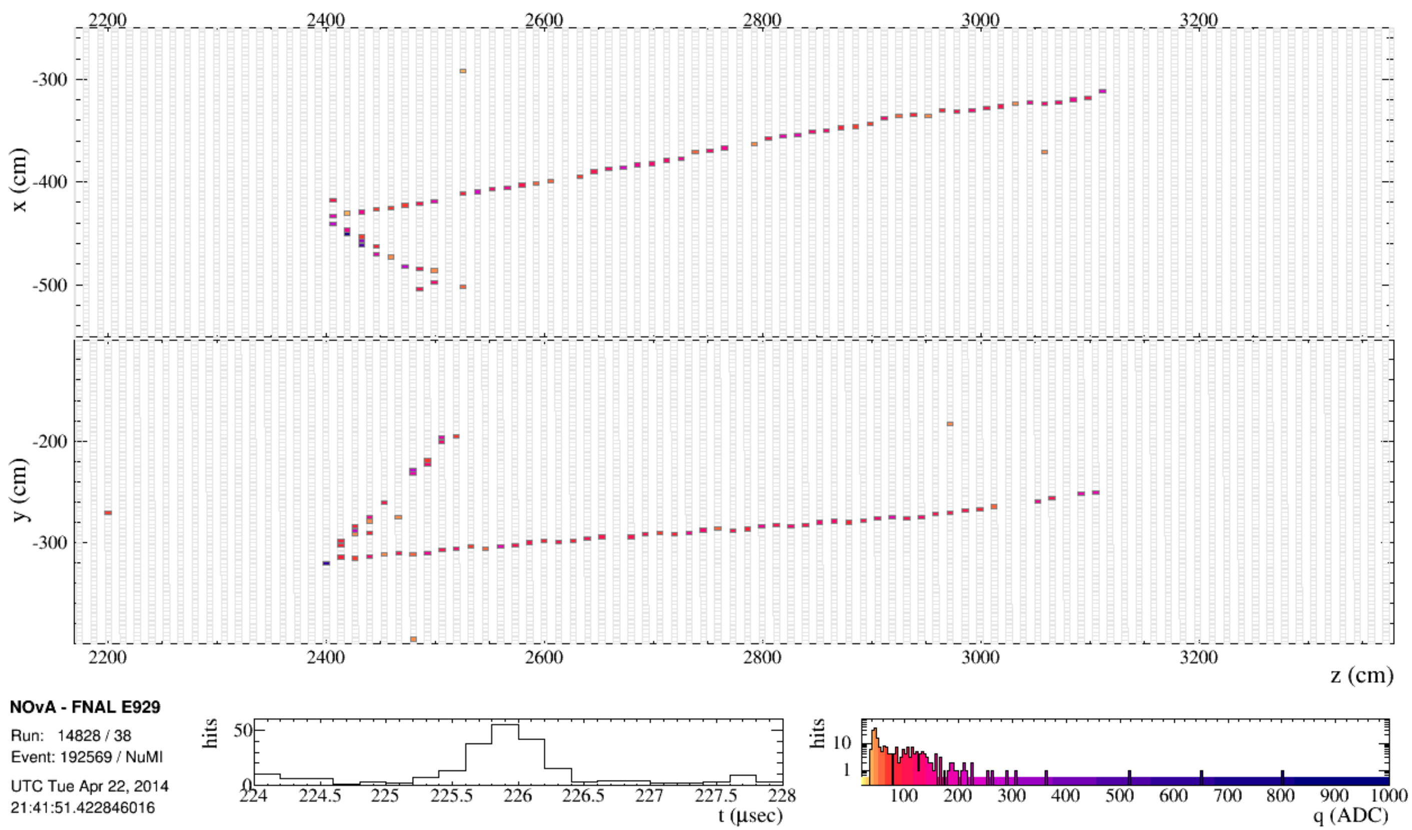
- Because hits in a trigger window are a combination of cosmic and beam events, first step in reconstruction is to cluster hits by space-time coincidence

Early far detector data from a 550 us trigger window data.



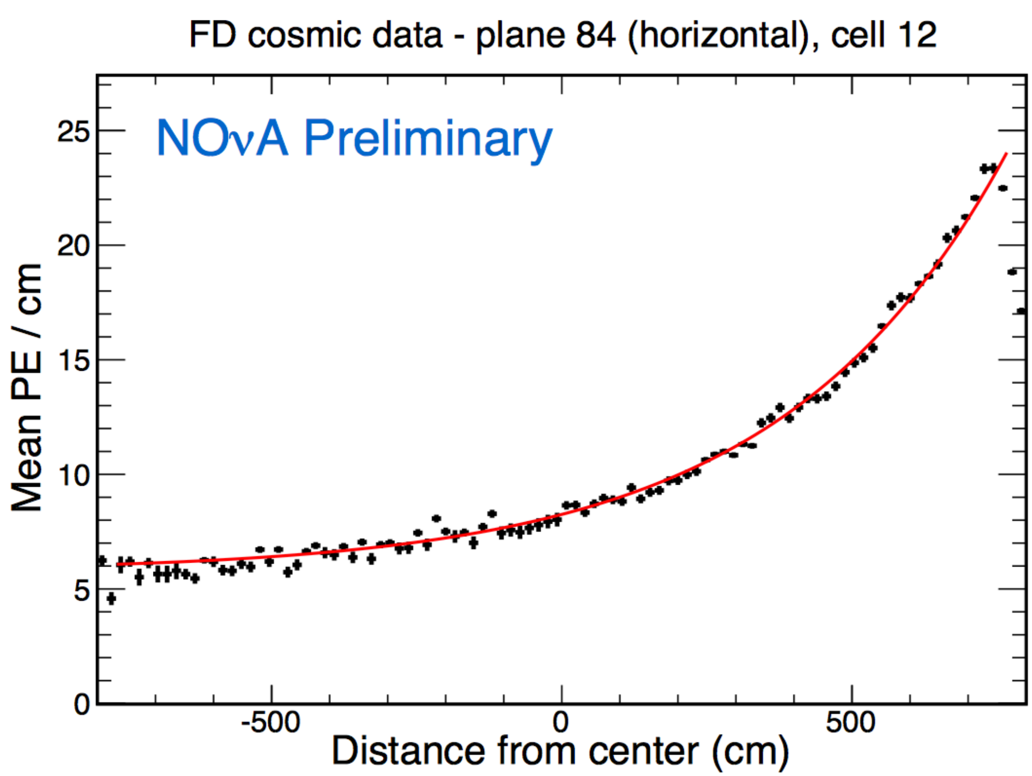
Space-time clustering

- After the space-time clustering, we are able to pick up the single space-time cluster for the beam event in a trigger window.



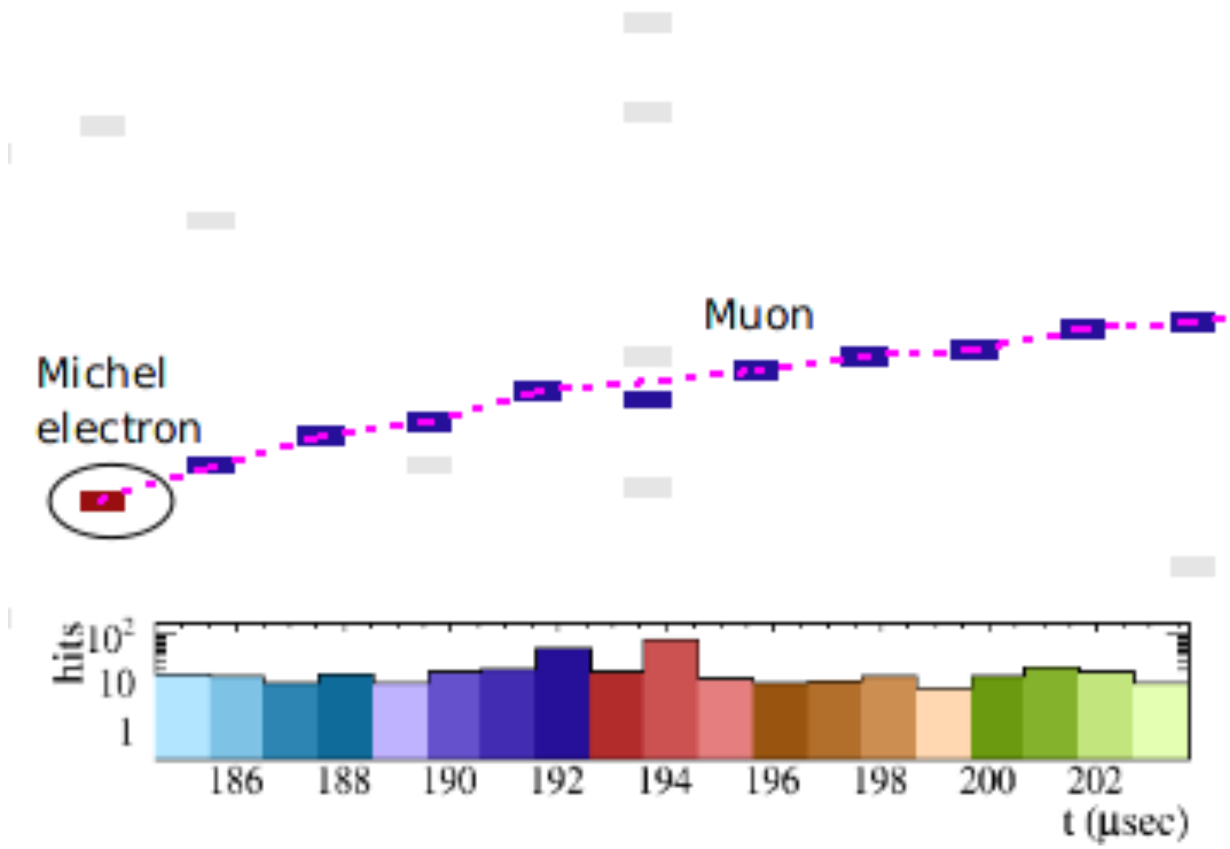
Cell Calibration

- Cosmic ray data is used to correct for the fiber attenuation in each cell.
- An exponential fit to the number of photo-electrons (PE) per path length gives the cell response as function of depth in the cell.
- Drift calibration applied to correct for temporal changes in the detector. Mean dE/dx measured in APDs weekly and normalized to baseline response.



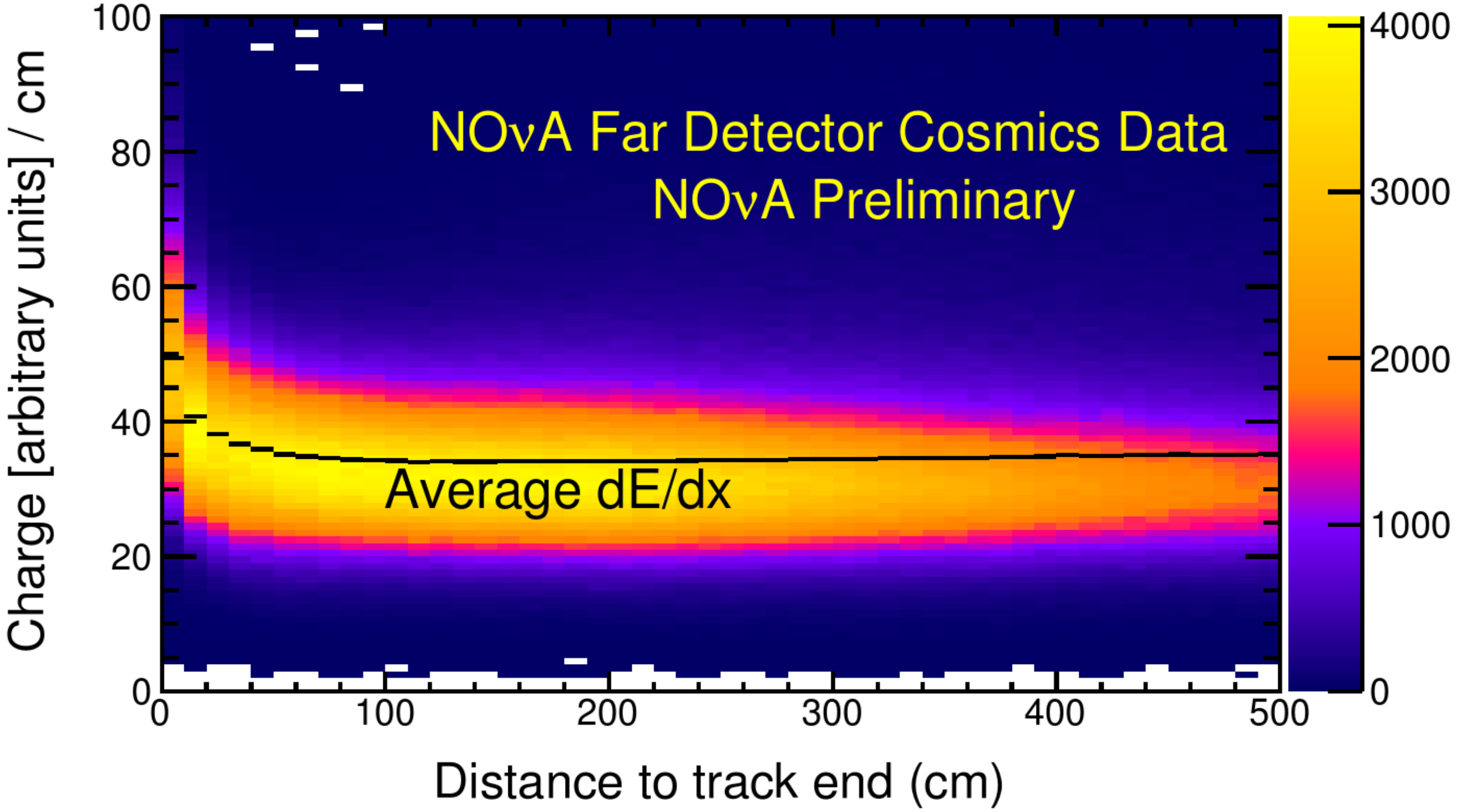
Absolute Energy Calibration

- Converts attenuation corrected signal into visible energy measurement.
- Absolute energy scale determined from stopping muons.
- Stopping muons tagged by Michel electron



Absolute Energy Calibration

- dE/dx measured between 100 and 200 cm from the track end.
- Simulation is tuned to match the measured dE/dx from data.
- Absolute energy scale is obtained from tuned simulation.



ν_e appearance analysis

- ν_e event reconstruction: reconstruct event vertex and prongs (showers).

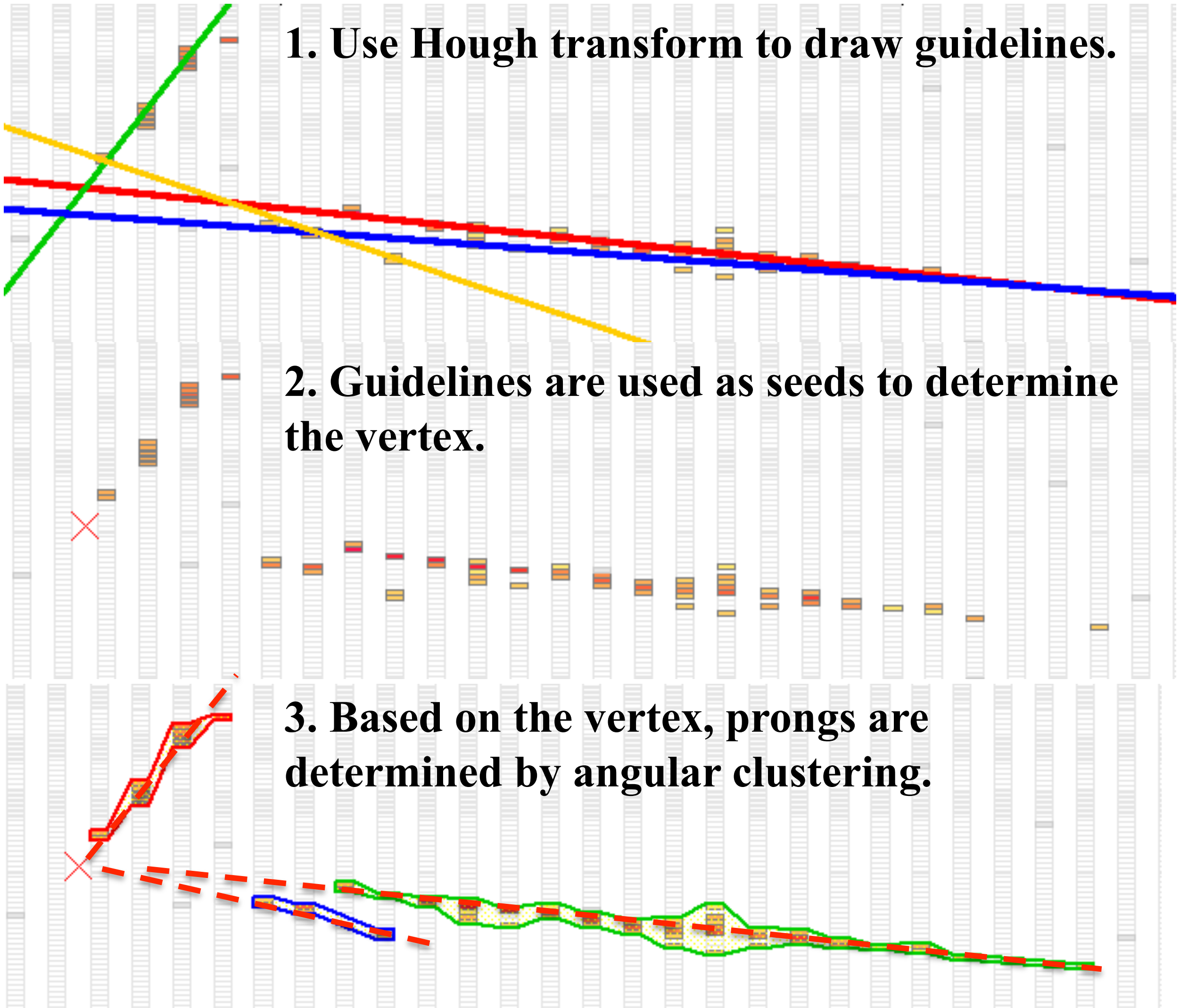
- ν_e identification: identify ν_e in $\nu_\mu \rightarrow \nu_e$ oscillation
  - ANN: Artificial neural network using shower shape based likelihood for particle hypotheses.
  - LEM: Matching events to a Monte Carlo library.

- Decomposition.

- Extrapolation.

- Sensitivity studies.

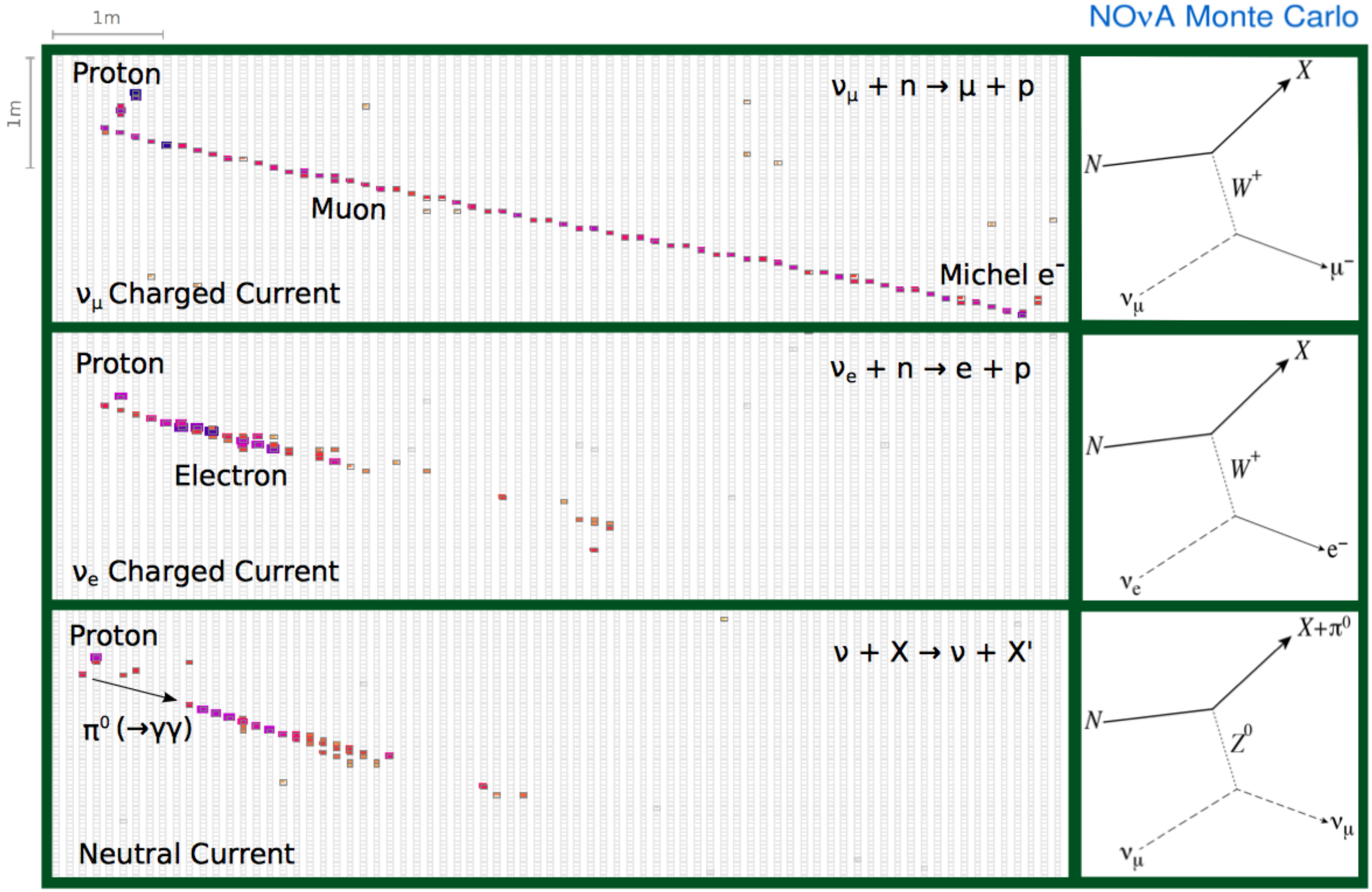
ν_e event reconstruction



ν_e identification (ANN)

- Identify the electron in ν_e-CC final states from various backgrounds.
- The basic idea is to use shower energy profile to separate electron from $\mu/\gamma/\pi^0$ and other hadrons.
- Different particles have very different energy deposit behaviors in the detector, which makes it possible to identify particles by comparison of shower shapes with different particle hypotheses.

Neutrino Event Topology in NOνA



The muon is a long minimum ionizing particle (MIP) track, the electron ionizes in the first few planes then starts a shower and the photon is a shower with a gap in the first few planes.

ν_e identification (ANN)

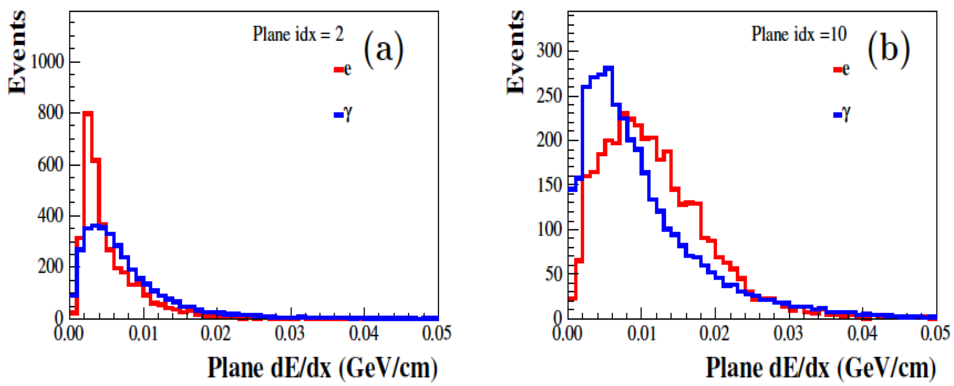


FIG. 8: Longitudinal dE/dx for electrons (red) and photons (blue): (a) Plane index = 2; (b) Plane index = 10.

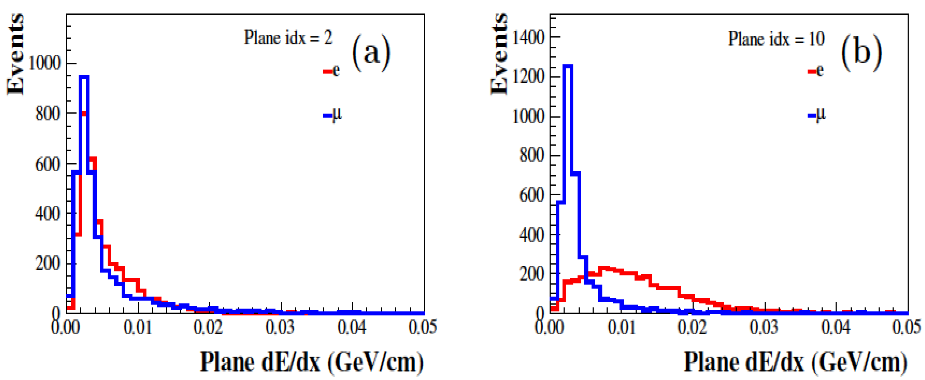


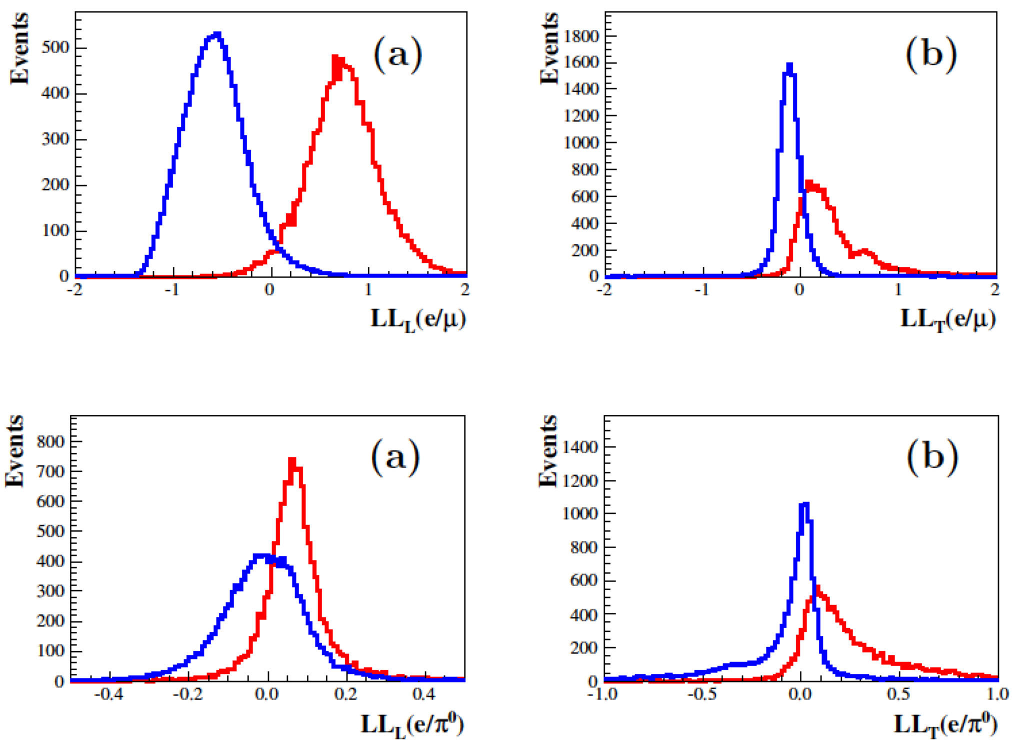
FIG. 9: Longitudinal dE/dx for electrons (red) and muons (blue): (a) Plane index = 2; (b) Plane index = 10.

- **We use dE/dx to describe energy profile of particles.**

- **Calculate the longitudinal dE/dx by plane and calculate the transverse dE/dx by transverse cell index.**

- **Simulation is used to make expected distributions of the dE/dx for each particle hypothesis**

ν_e identification (ANN)

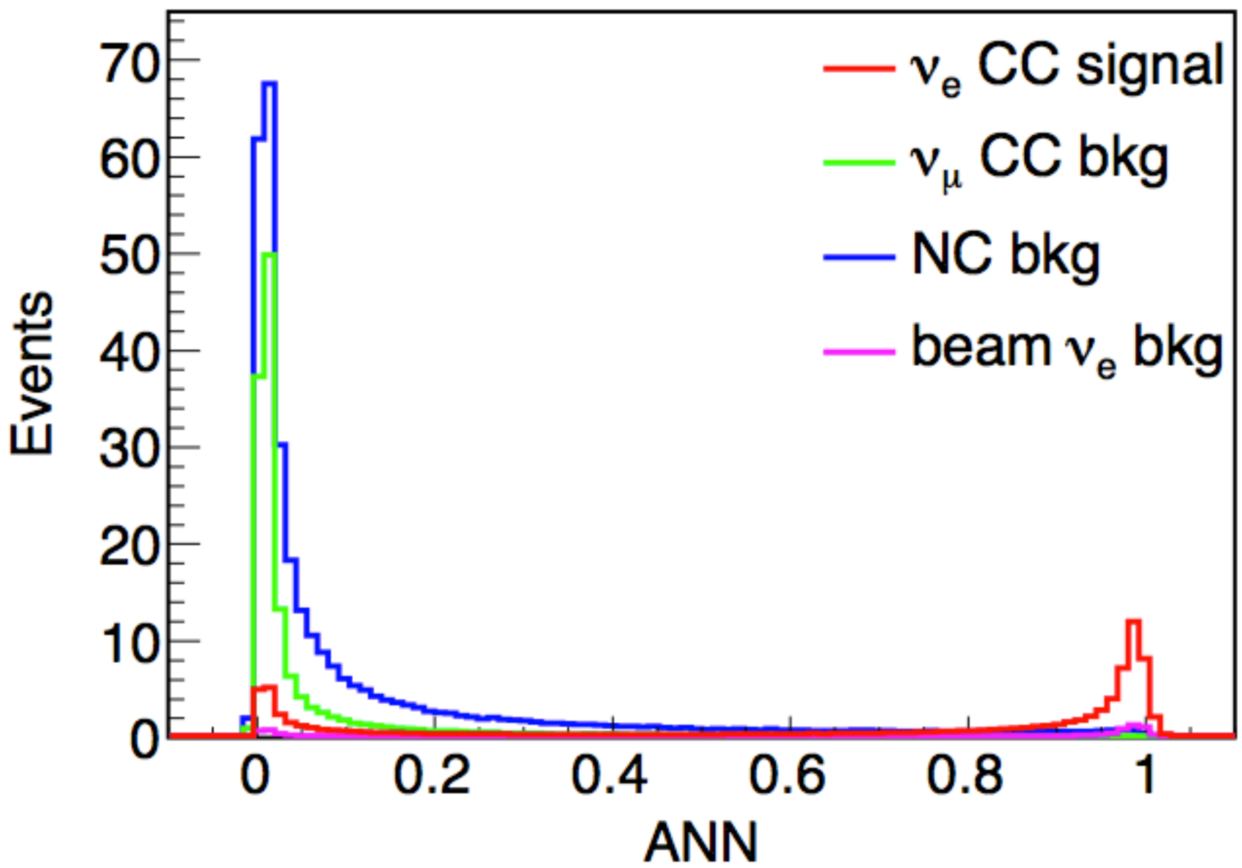


- For an unidentified particle, we compare its dE/dx with the expected dE/dx histograms by each plane and transverse cell index to construct the probability and likelihood for each particle hypotheses.

- Summing over these plane-by-plane and cell-by-cell likelihoods we have overall longitudinal and transverse likelihoods for each type of particle.

- The difference of log-likelihoods indicates the identity of the particle, for example: $LL(e/\mu)=LL(e)-LL(\mu)$.

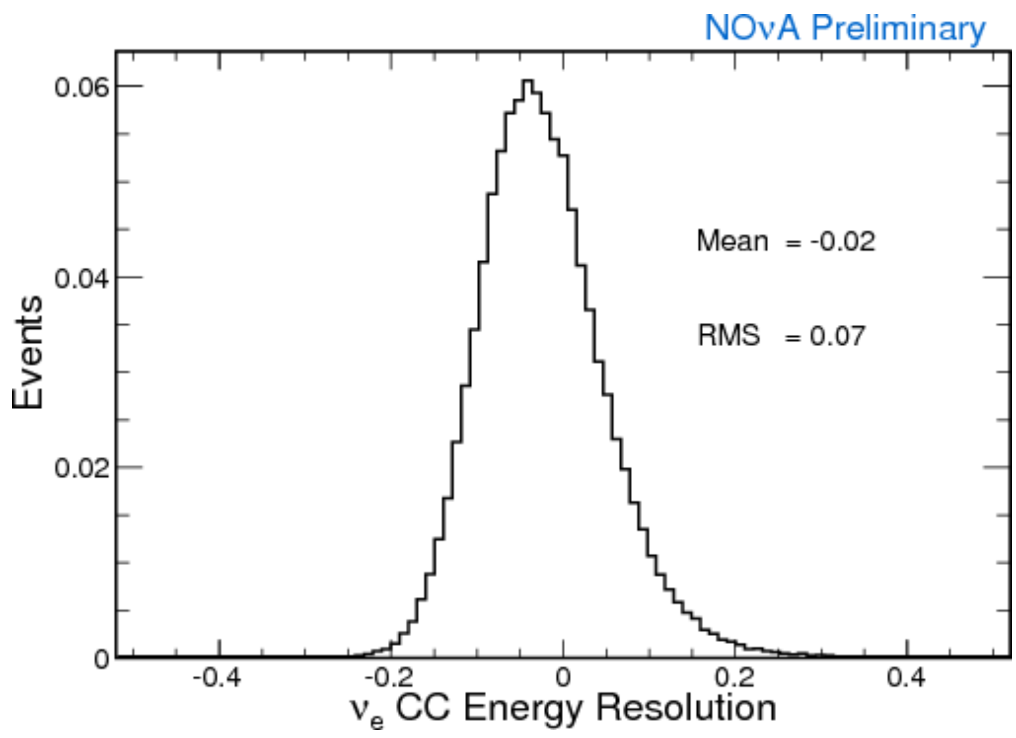
ν_e identification (ANN)



- These longitudinal and transverse log likelihoods, amongst other variables, are used as inputs to a Artificial Neural Net (ANN) for the final PID.

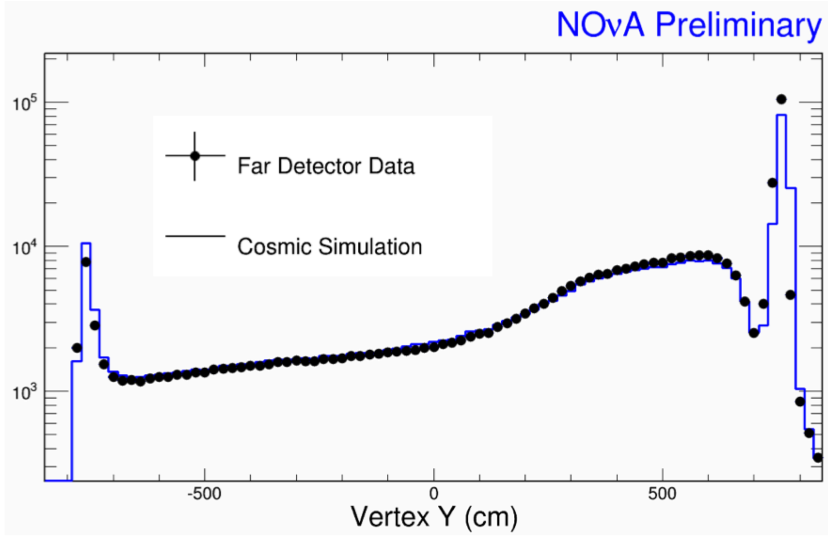
ν_e Energy

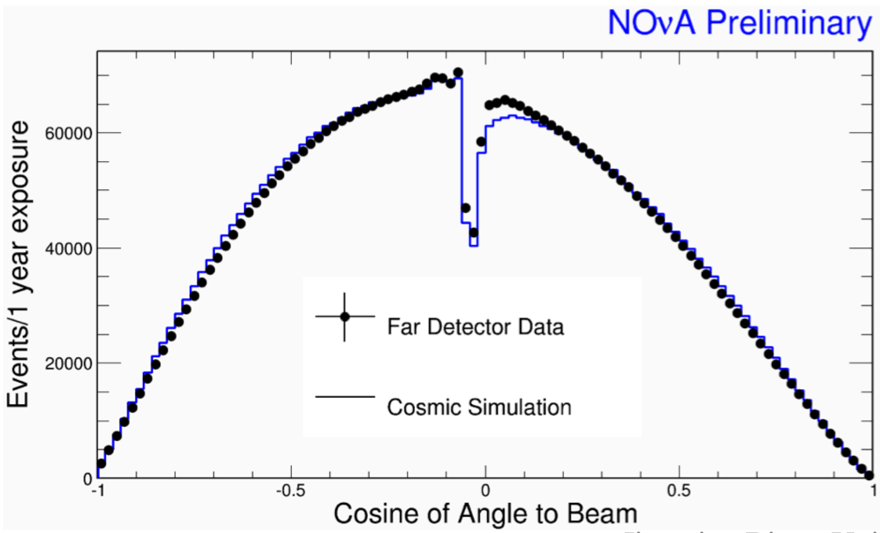
The calorimetric energy resolution for ν_eCC events with ANN > 0.95 is 7%.

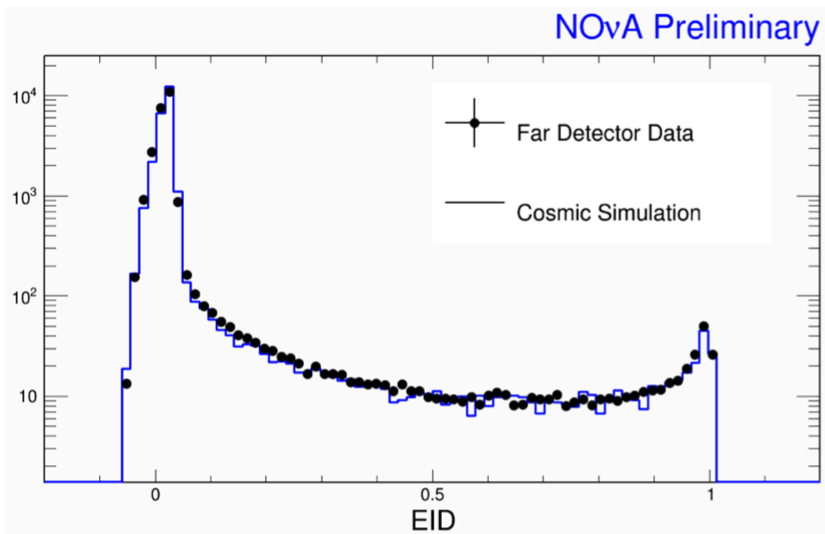


Data/MC comparison

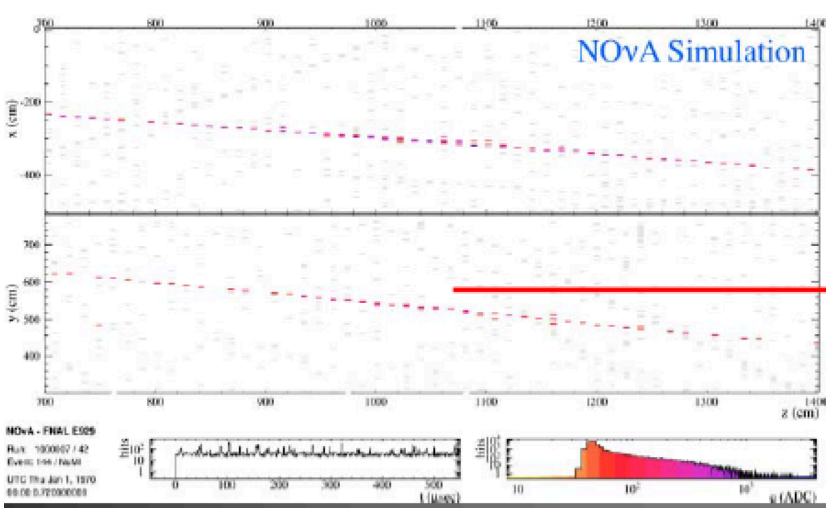
- Using real cosmic ray data for comparison, we verify our simulation and detector modeling.
- Reconstruction variables and PID output has been validated for muon in cosmic rays.

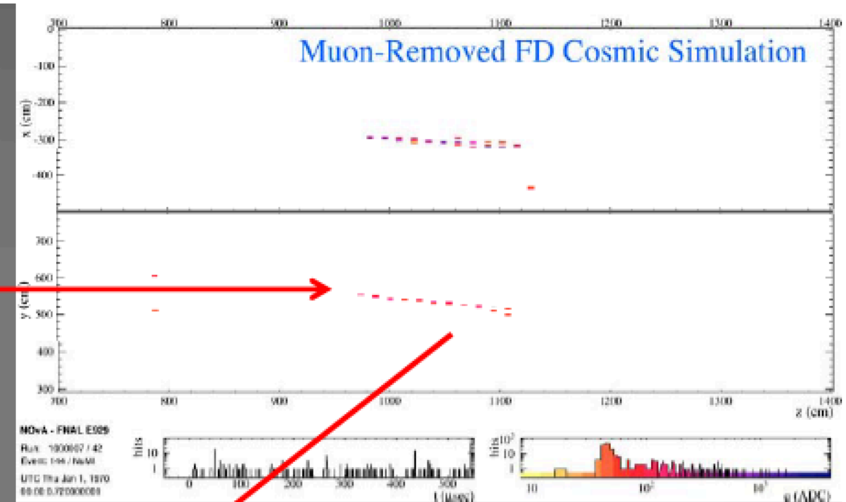


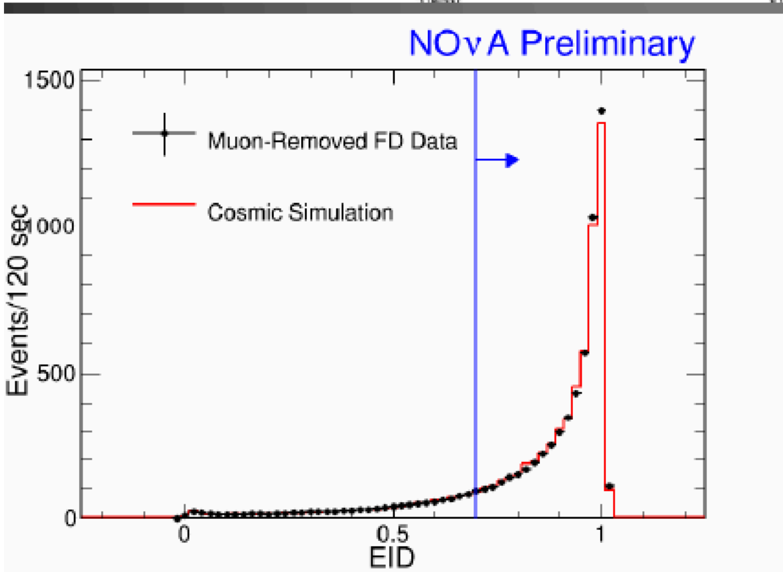




Data/MC comparison



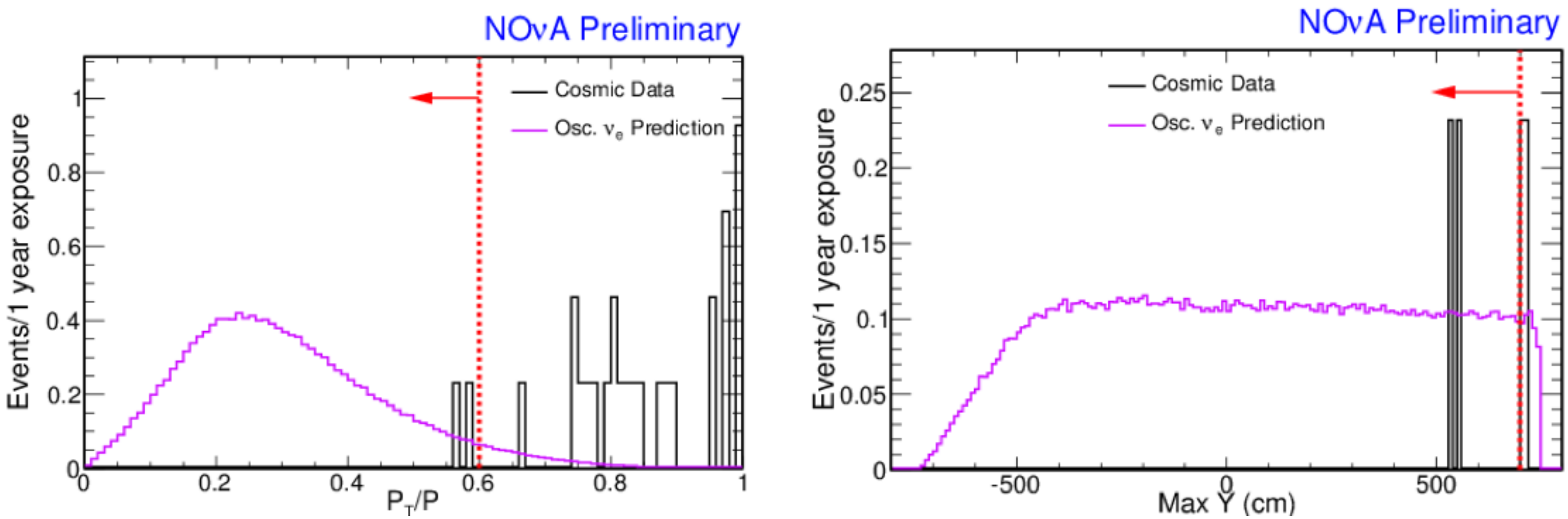




Extract EM shower from CR muon events, and compare EID, etc, with expectations from simulation.

Allows us to validate our signal event modeling without opening the box on FD neutrino events.

Cosmic Rejection for ν_e

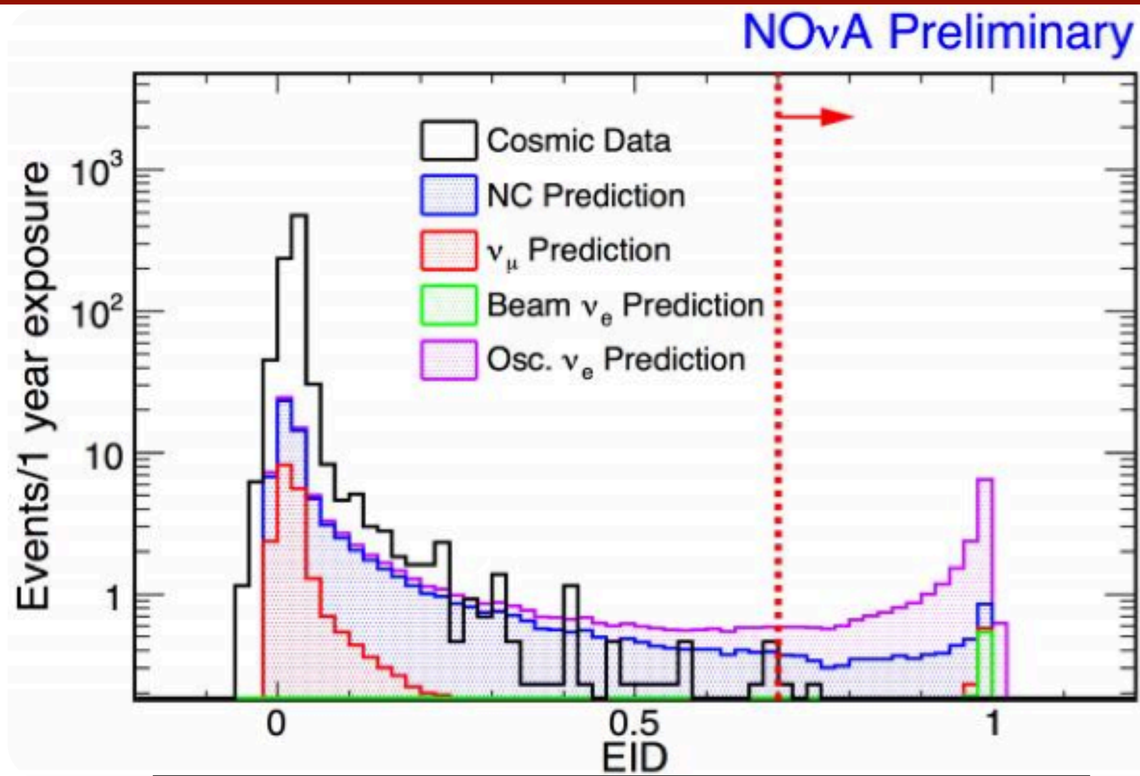


Because the NOvA FD is on surface, the rejection of cosmic rays is extremely important.

Three simple cuts are used to reject the cosmic induced backgrounds prior to PID

- *P_t/P* - force directionality of showers along the beam
- *Max Y hit position* – remove particles entering from the top of the detector
- Vertex Gap – assure reconstruction quality

Event selection (cosmic rejection)



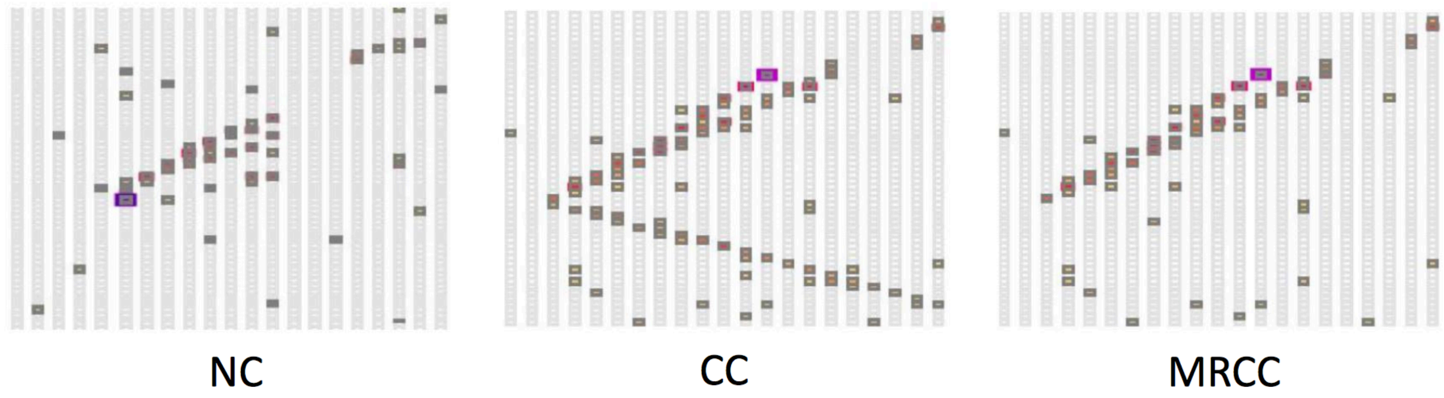
	Osc ν_eCC	Beam Bkg	Cosmic Bkg
1 yr Nominal Exposure			
	36.7	965	19M
Containment & quailty	24.7	106	55k
Cosmic Rejection	21.2	82.9	834
ν_e selection	13.9	6.0	0.46

<u>Achieves 40 million to 1 cosmic rejection</u>

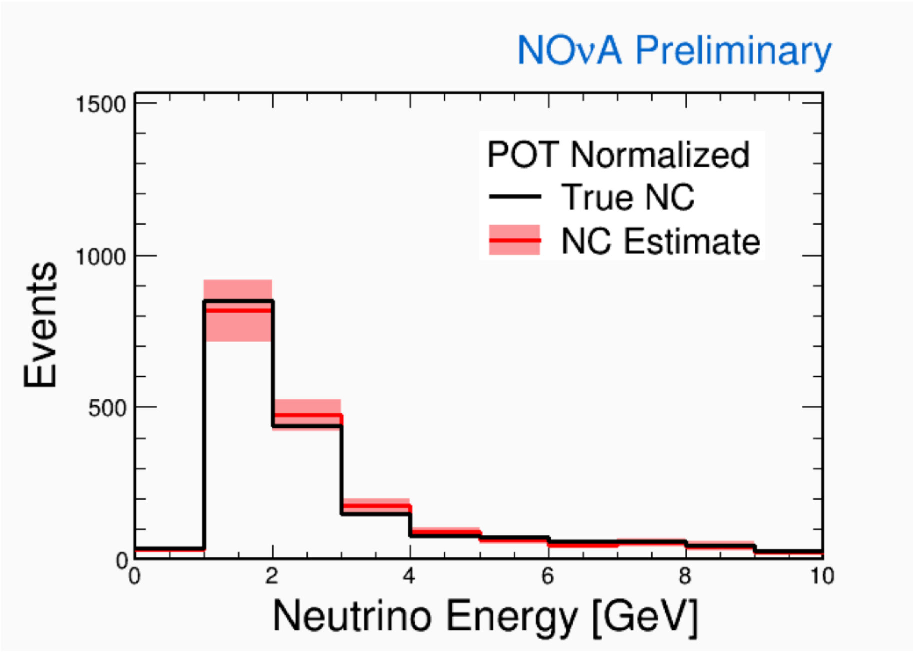
Background Estimate

- Because of neutrino oscillations, the far detector background will not have the same shape as the background in the Near Detector.
- To isolate the NC, CC, and Beam-ν_e components in the Near Detector we need a data-driven decomposition.
- Once we have a decomposition, we can extrapolate each of these components to the Far Detector.

Muon-Removed Charged Current Decomposition (MRCC)

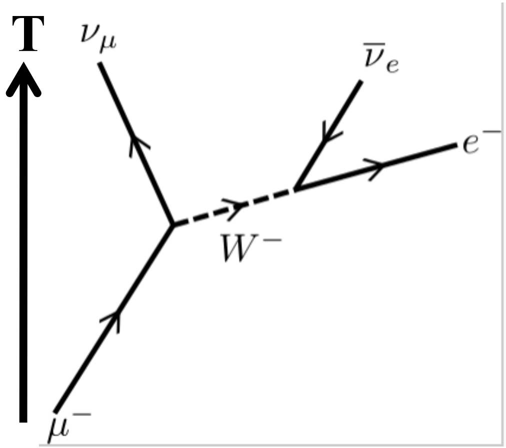


- Because NC events are hard to identify, we use the muon-removed ν_μ CC sample to estimate the NC background.
- A ν_μ CC event produces a long μ track and hadronic showers in our detector.
- Remove the μ track in the event and use remaining hadron showers to mimic a NC event.
- The MRCC spectrum in data is scaled by a MC factor to give a NC estimate.

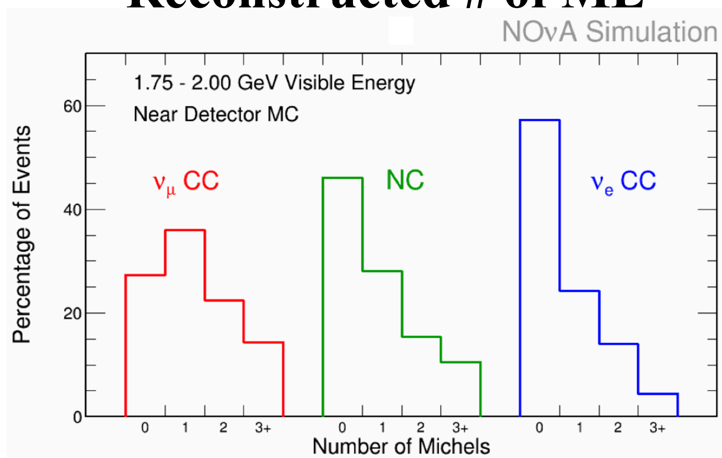


Michel Electron Decomposition

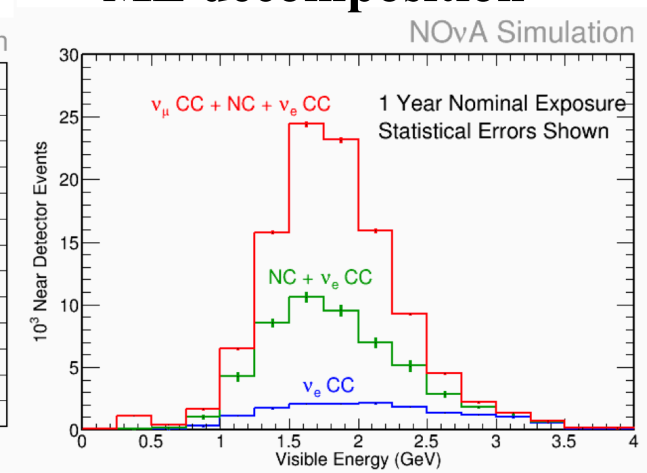
Michel decay of muon



Reconstructed # of ME



ME decomposition



- A ν_μ CC event will have a Michel electron from the primary μ.
- Different type of backgrounds have different numbers of reconstructed Michel electron.
- In each energy bin, we perform a χ^2 fit scaling MC distributions of number of Michel electrons to data to determine yields of ν_μ-CC, NC and ν_e-CC.

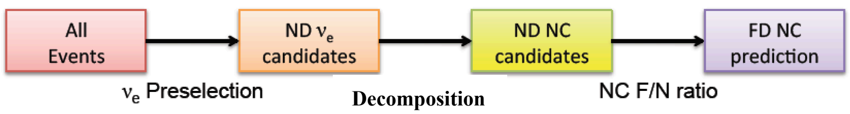
Extrapolation

- NOvA Near Detector and Far Detector are designed similarly to share event efficiencies and purities, and cancel systematic errors.
- Different flux and volumes cause FD and ND events have different kinematics.
- F/N ratios in MC are applied to near detector data to predict far detector spectrum.

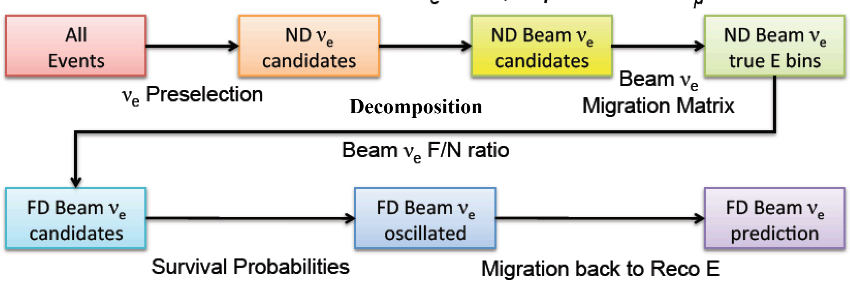
Extrapolation

Survival Method used for events that occur in both detectors (from preselected ν_e candidates)

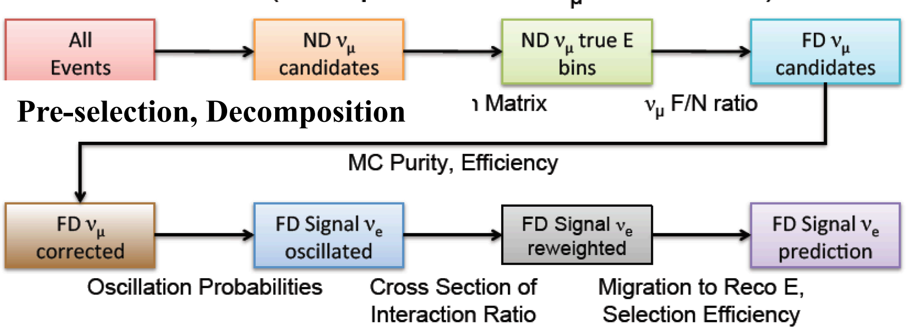
Survival Method for NCs

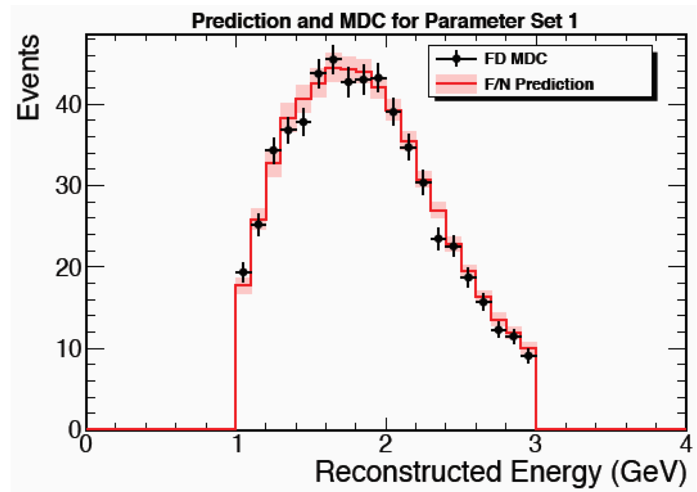


Survival Method for Beam ν_e CCs, repeated for ν_μ CCs

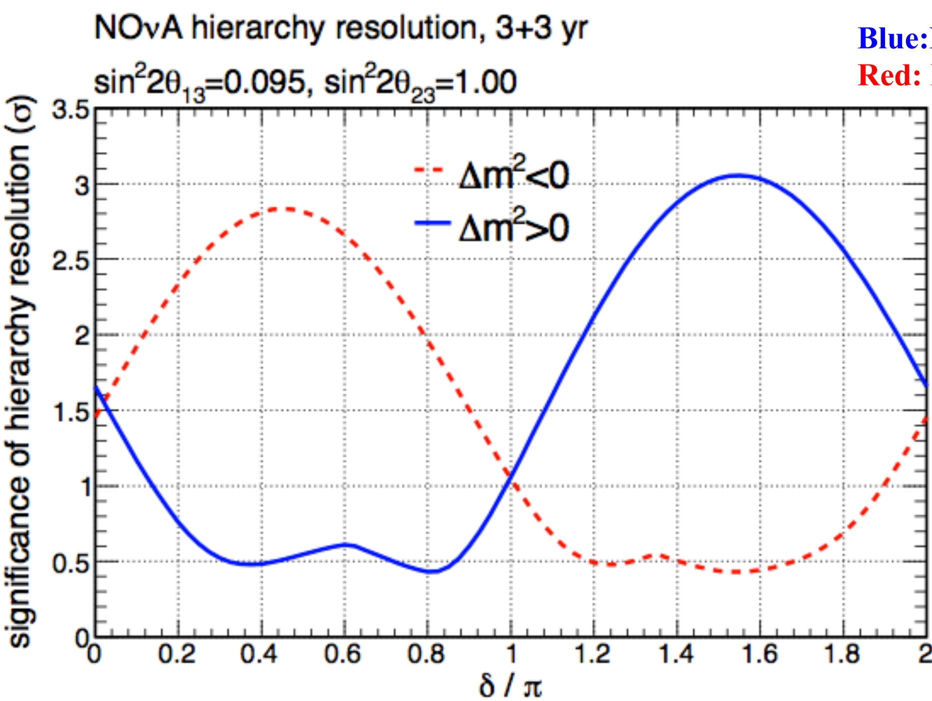


Appearance Method used for signal ν_e CCs and background ν_μ to ν_τ CCs, events which only occur at far detector (from preselected ν_μ candidates)

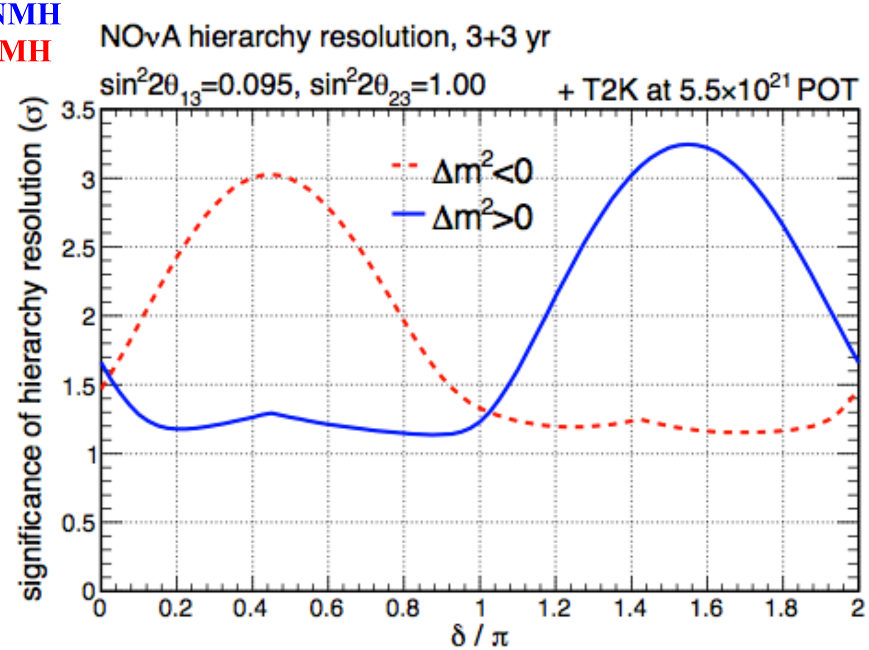




Significance to resolve mass hierarchy



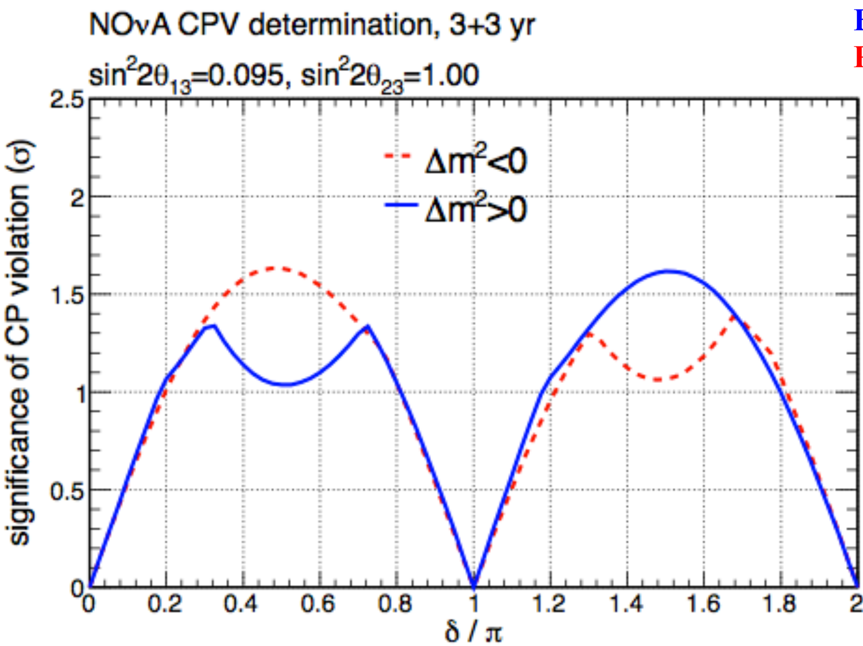
Blue:NMH
Red: IMH

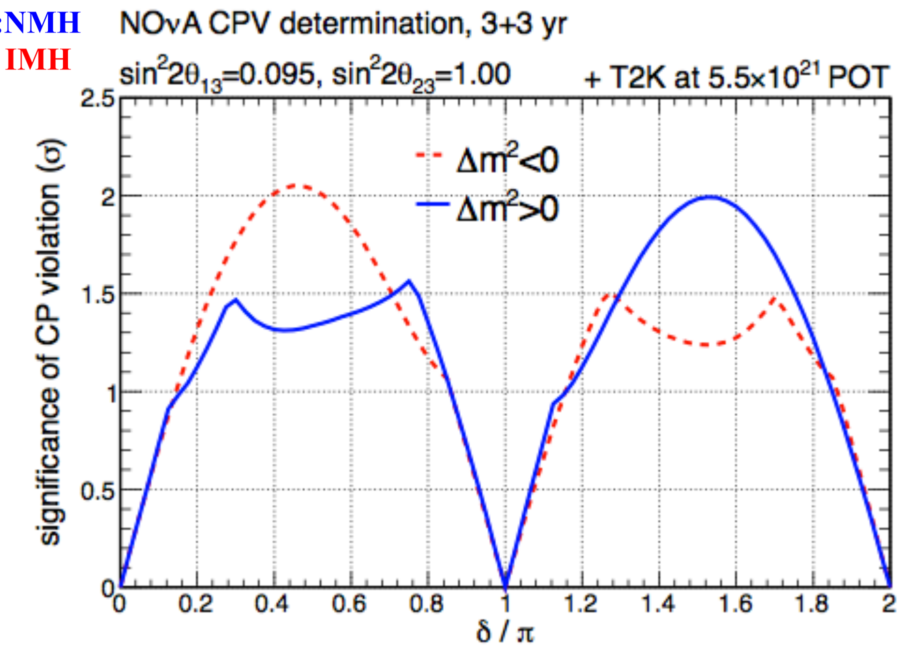


- After having the extrapolated signal and background predictions in the far detector, we fit to PID/Energy distribution to study sensitivities.

CP violation phase

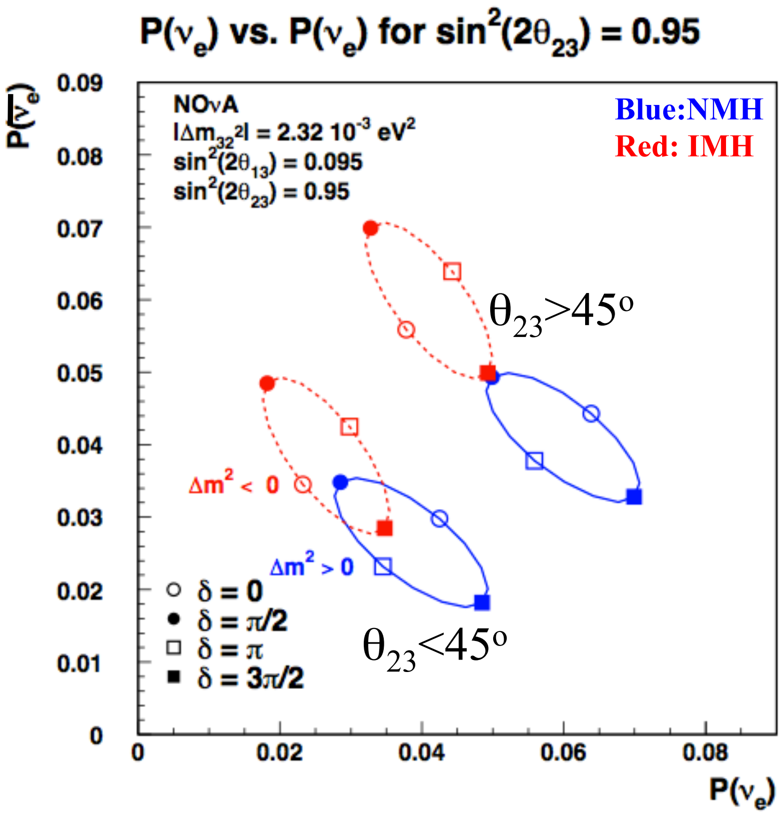
Blue:NMH
Red: IMH

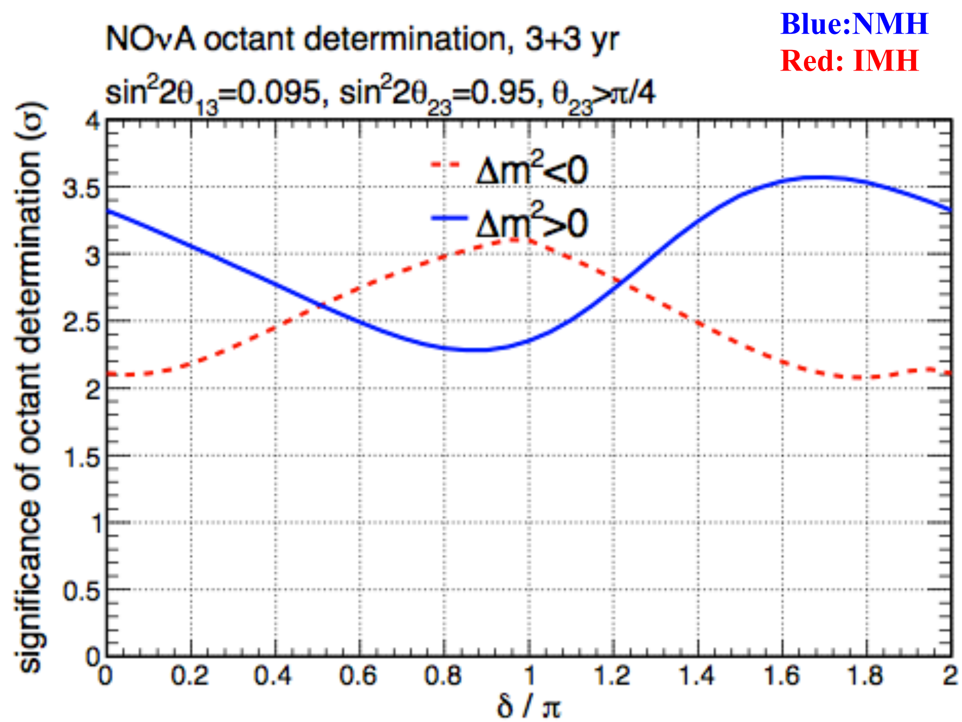




- Results from full simulation, reconstruction, selection, and analysis framework.

Octant of θ_{23}





- $\sin^2(2\theta_{23})$ is measured in ν_μ disappearance.
- If $\sin^2(2\theta_{23})$ is not maximal there is an ambiguity as to whether θ_{23} is larger or smaller than 45°.
- The $\sin^2(\theta_{23})$ term is crucial in comparing accelerator to reactor experiments.
- Because $P(\nu_\mu \rightarrow \nu_e)$ is in proportion to $\sin^2(\theta_{23})\sin^2(2\theta_{13})$, it can be used to determine θ_{23} octant.

ν_μ disappearance analysis at NOvA

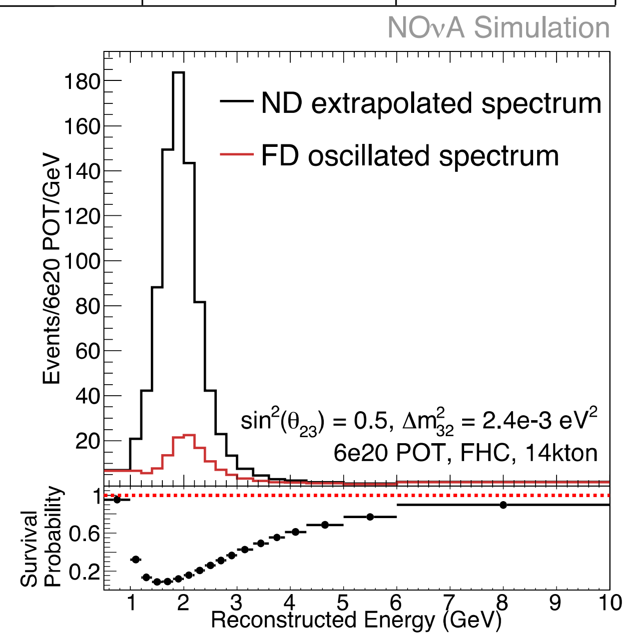
ν_μ Signal and Background Estimates

	Simulation					Data	
Cut	Un-Osc. ν_μ	Osc. ν_μ	NC Bkg	Osc. ν_e	Beam ν_e	Cosmic Bkg	Total Bkg
All Events	669	127	380	37	10	19M	19M
Cosmic Veto	660	125	273	36	10.0	6M	6M
Containment	582	109	195	28	7.5	120k	120k
ν_μ CC ID	460	86	5	0.4	0.2	44k	44k
Cosmic Reject	398	**75**	4	0.3	0.1	1	**5.4**

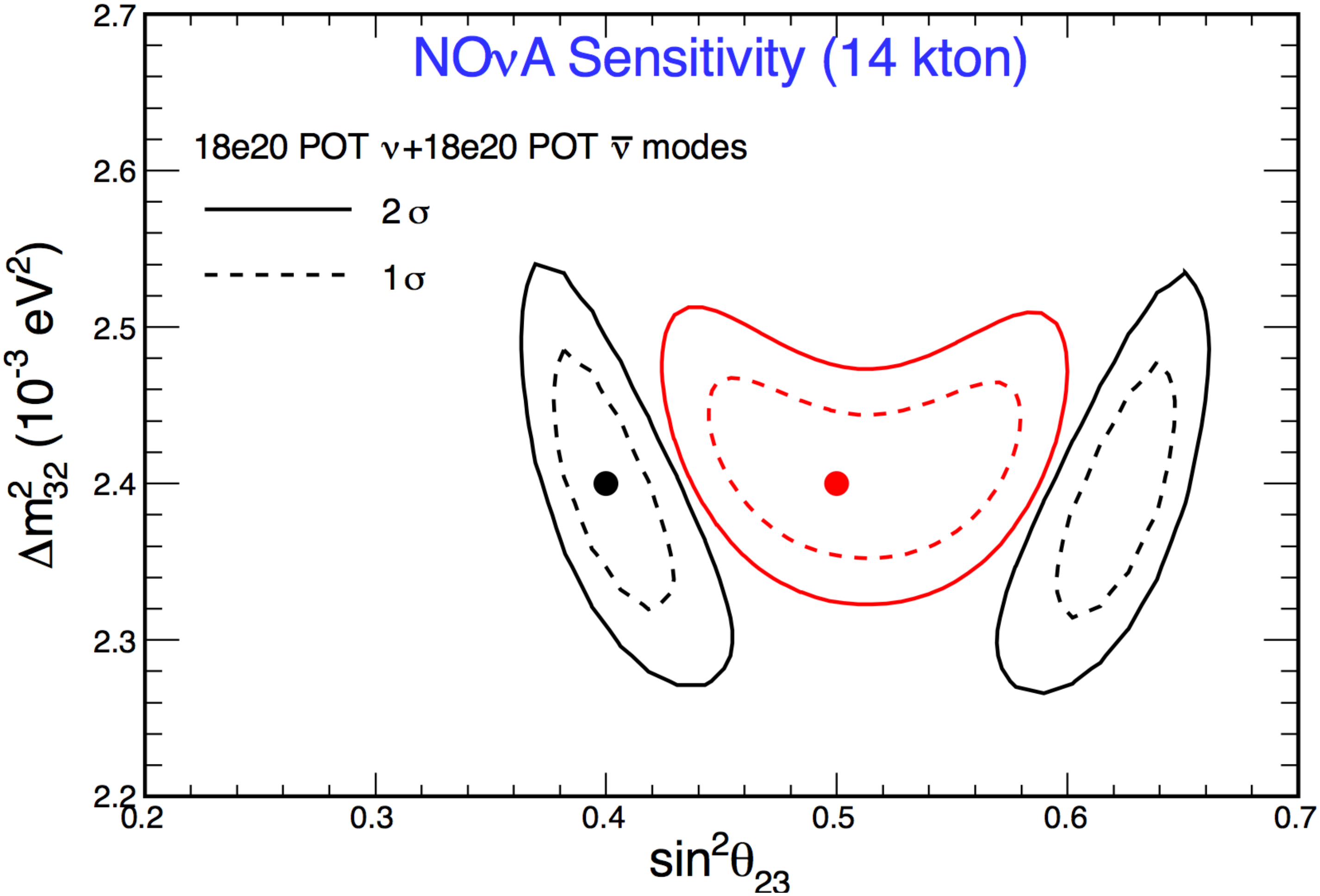
- Exposure 6×10^{20} POT
- 14 kt total detector mass

Multiple selection criteria:

- Event ID criteria separate ν_μ-CC from NC events.
- Boosted Decision Tree method for separating out cosmic background.
- Achieves cosmic rejection 20M:1.



ν_μ disappearance analysis at NOνA



Summary

- Physics reach:
  - NOνA has the best chance to investigate mass hierarchy.
  - Can determine θ_{23} octant.
  - Provide information on CP violation.
  - Look at other physics such as supernova, neutrino magnetic moment, monopoles and non-standard neutrino interactions.

- NOνA is now taking physics data!
  - The NOνA detectors are complete.
  - The NuMI beam continues ramp to full power.
  - ν's observed in far and near detector.
  - Analysis tools are in place.
  - Demonstrated cosmic rejection 40 million to 1.
  - We are working towards first physics results in 2015.

Thank you!

Backup

Liquid Scintillator

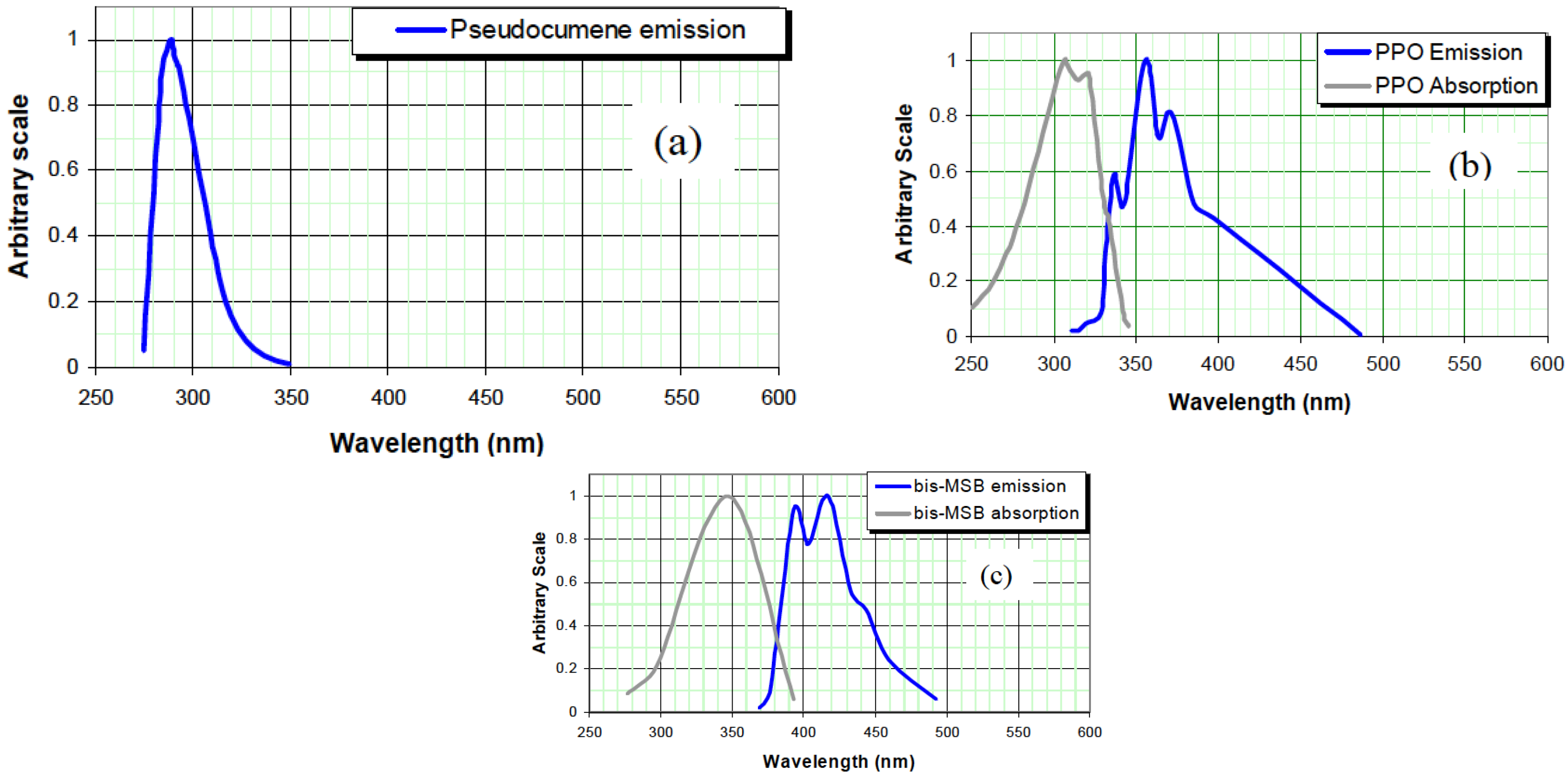
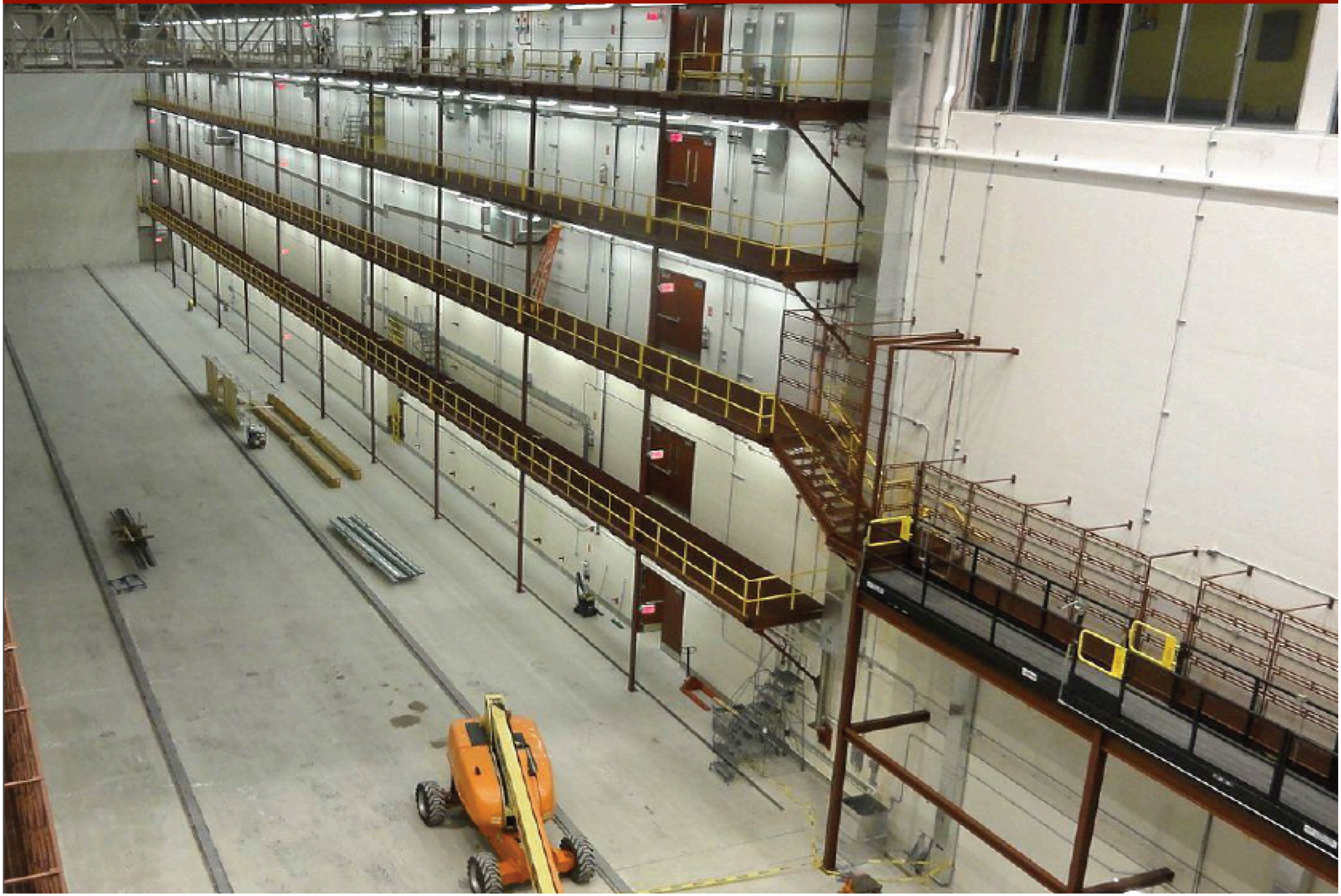


Fig. 10.1: Light production by liquid scintillator. The emission spectrum of the primary scintillant psueudocmene when traversed by an ionizing particle is shown in (a); the absorption and emission spectrum of the first waveshifter PPO is shown in (b); the absorption and emission spectrum of the second waveshifter bis-MSB is shown in (c).

Far detector construction

Far detector construction

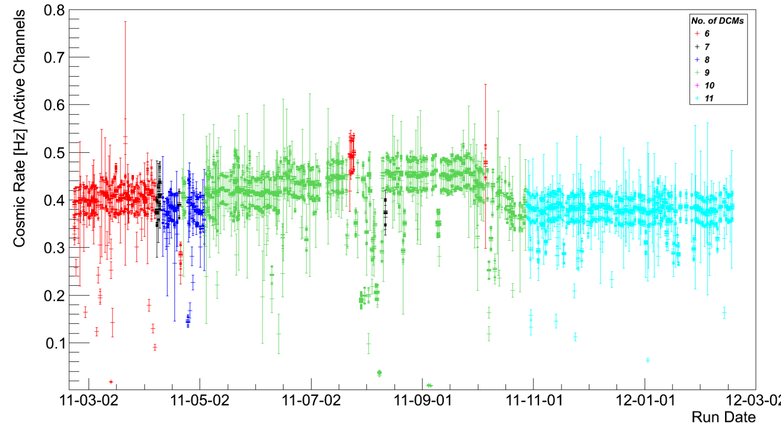


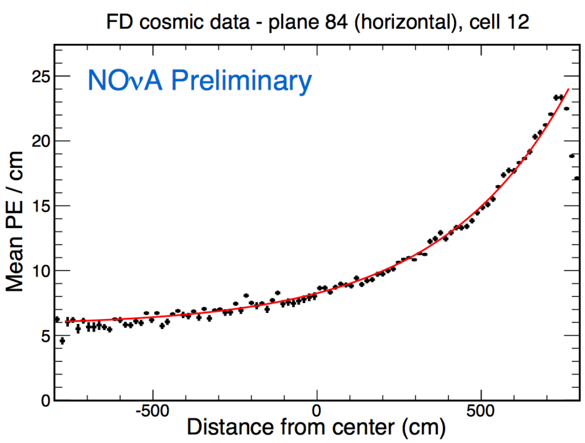
Far detector construction

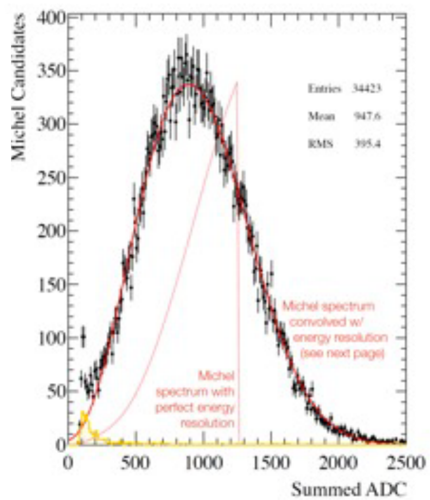
Far detector construction

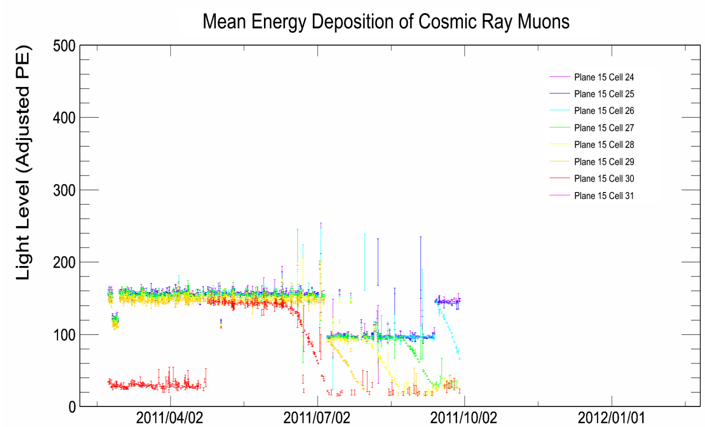
NOvA Calibration/Comissioning

- **Commissioning and calibration techniques:**
  - **Cosmic rate per number of active channels and light level as a function of of time.**
  - **Use cosmic rays to calibrate position dependence of cell response (light attenuation)**
  - **Michel electrons to calibrate low energy response.**

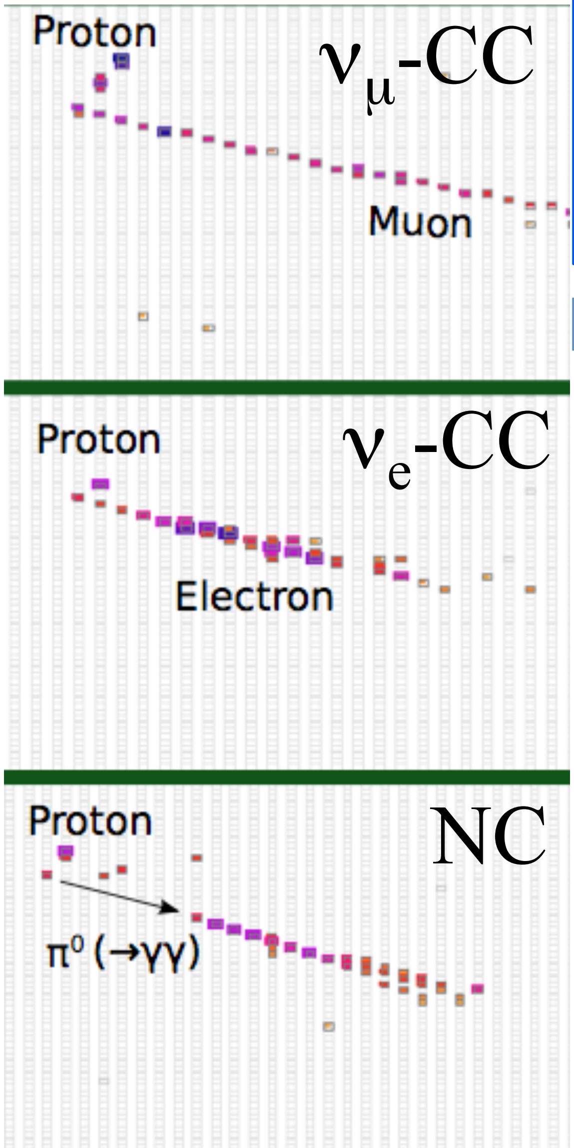




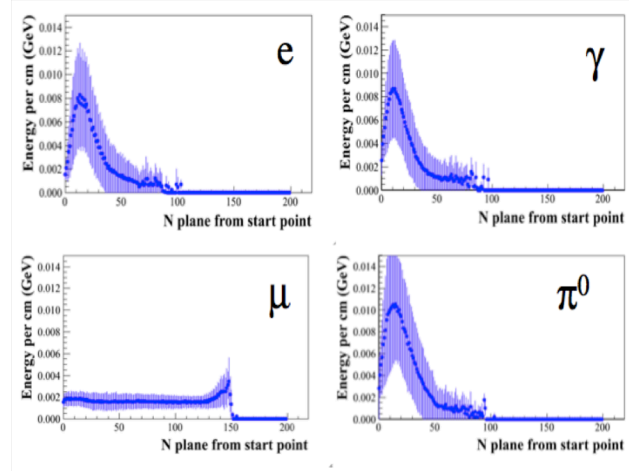




ν_e identification (ANN)

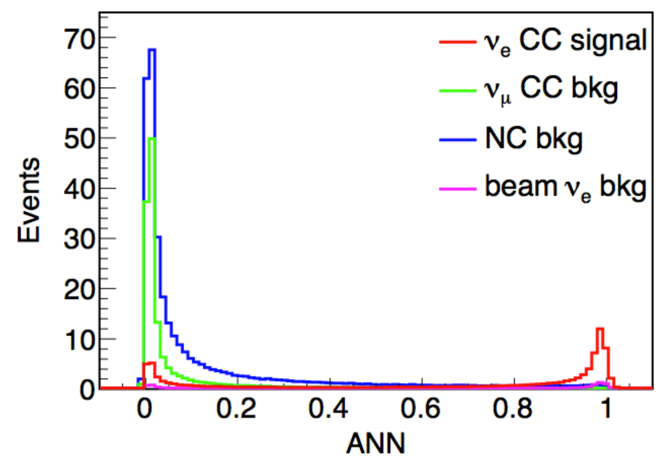


Parameterize energy profile by transverse/longitudinal dE/dx, then likelihood for particle hypotheses.

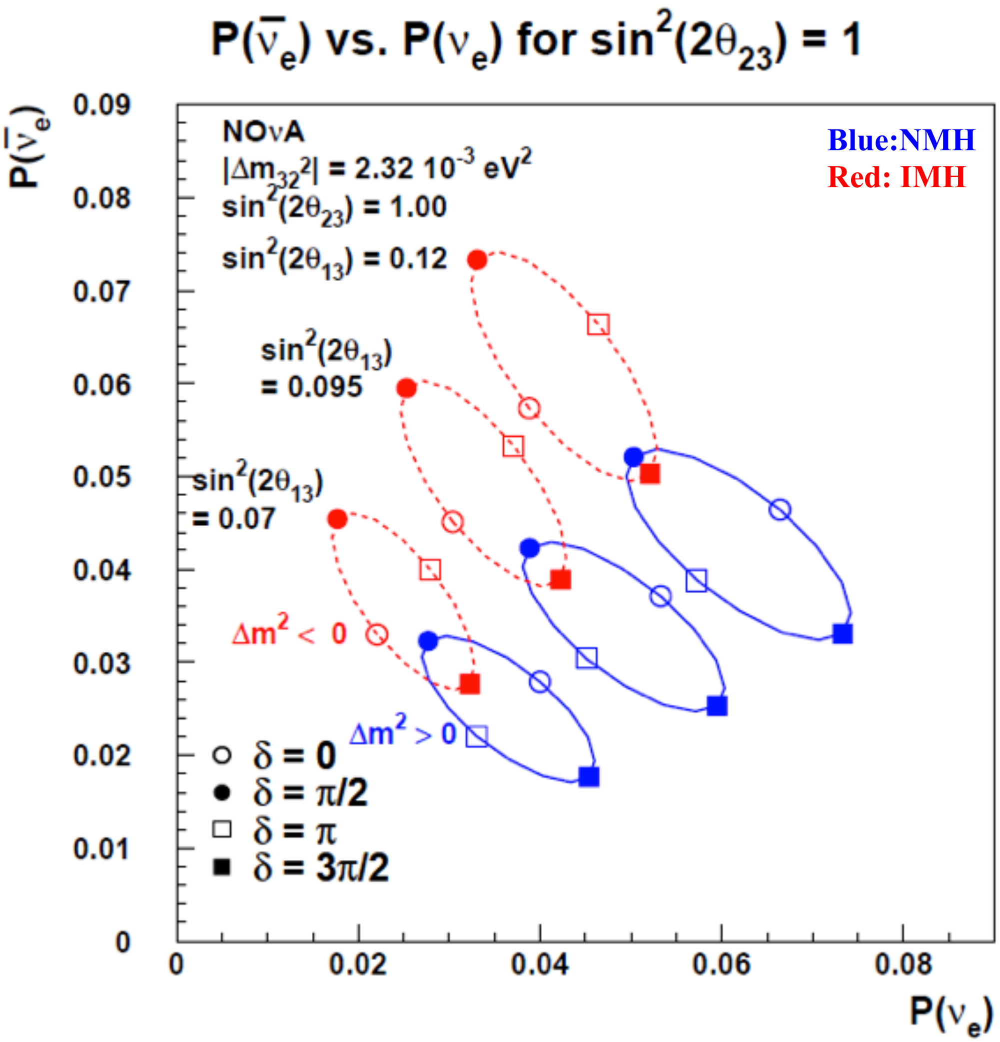


Combine shower shape information with an artificial neural network.

Because NOvA has fine-grained detectors, we are able to see details of energy profiles for different particles.



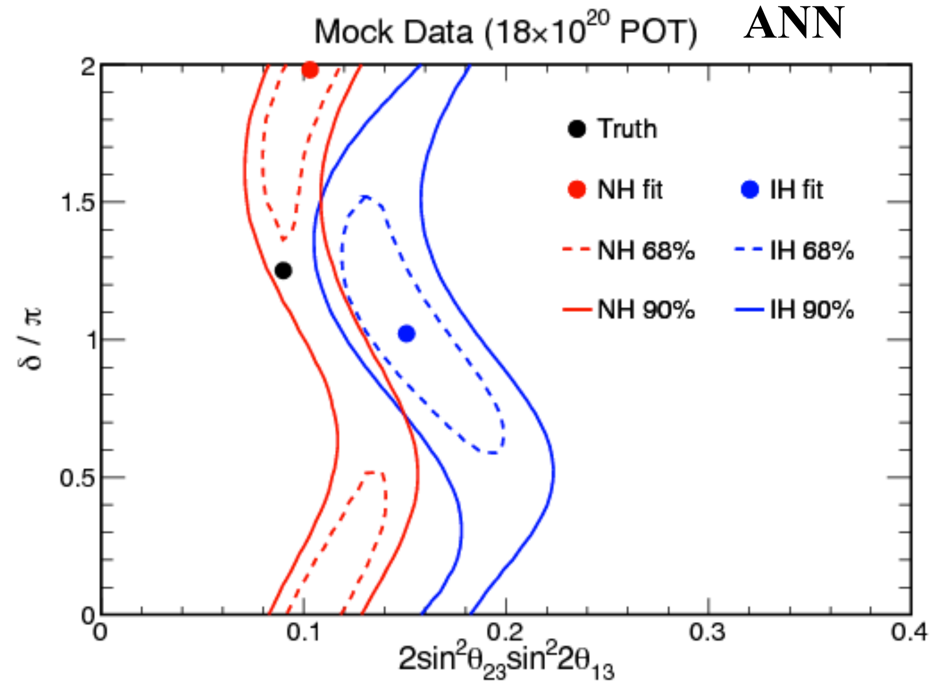
$P(\nu_e)$ vs. $P(\overline{\nu}_e)$ with different θ_{13} assumptions



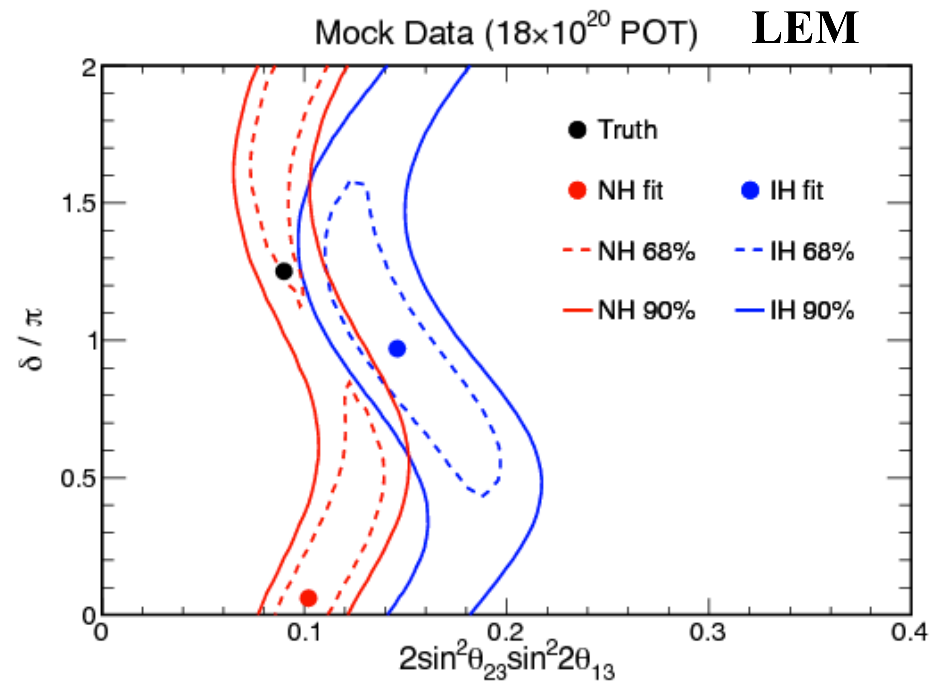
Mock data challenge– ν_e analysis

Mock data challenge for the first 3 years' data taking. Hidden physics parameters were chosen and all truth information was stripped from the Monte Carlo files. The two analysis techniques got identical results, which agreed with the truth within about 1σ.

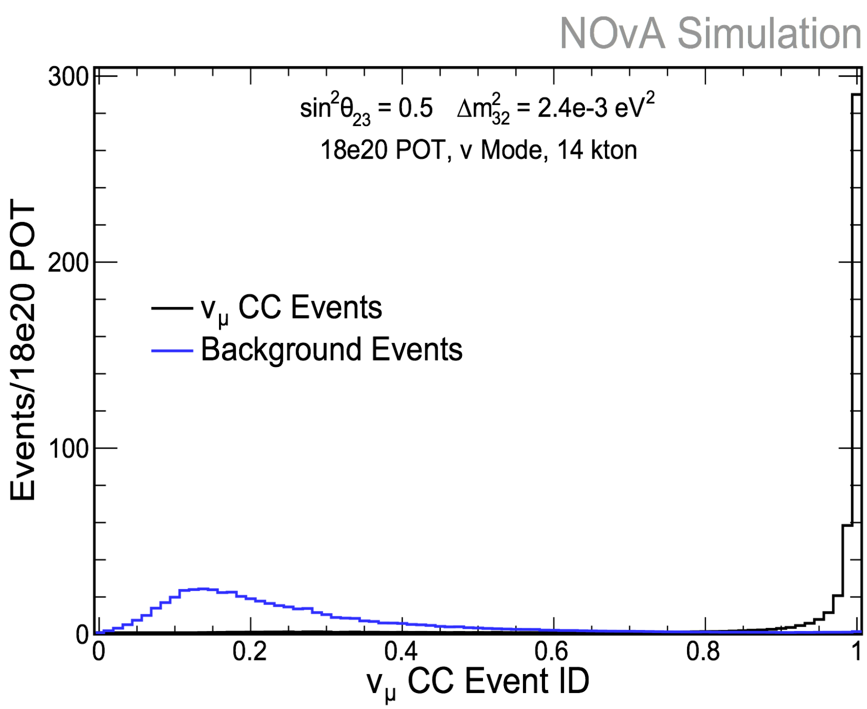
ANN

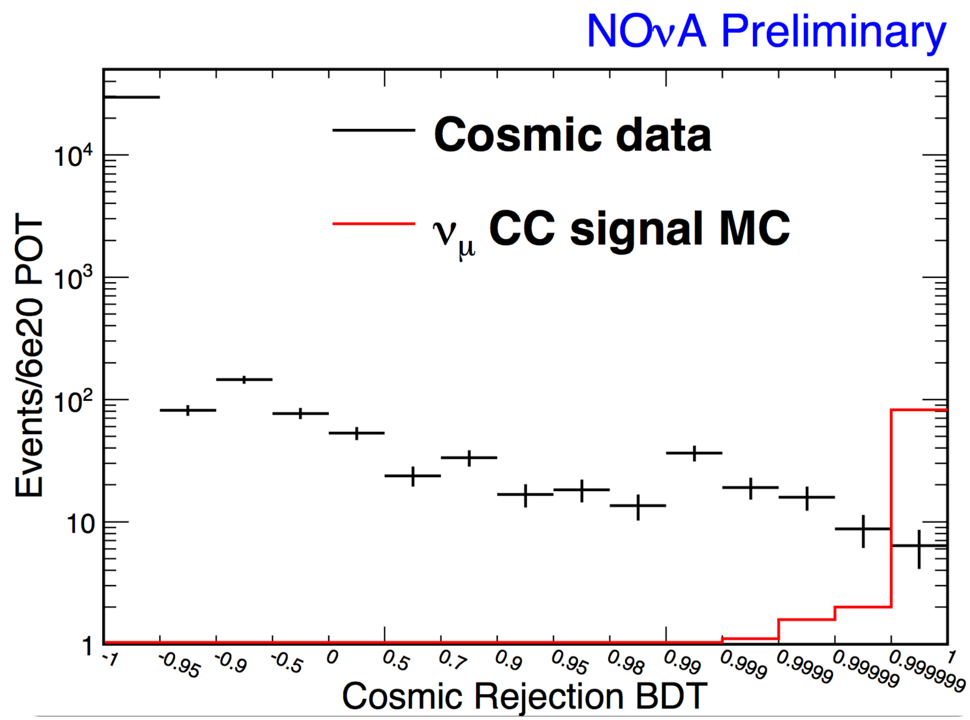


LEM



ν_μ disappearance analysis at NOνA





Multiple selection criteria:

- **Event ID criteria separate ν_μ-CC from NC events**
- **Boosted Decision Tree method for separating out cosmic background**
- **Achieves cosmic rejection 20M:1**